325
AUG 9 1963

ORNL-3450
UC-34 - Physics
TID-4500 (20th ed.)

EMISSION SPECTRA OF ELECTRON IRRADIATED

METAL FOILS

L. C. Emerson
E. T. Arakawa
R. H. Ritchie
R. D. Birkhoff

MASTER

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in USA. Price: \$2.75 Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

— LEGAL NOTICE —

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL-3450

Contract No. W-7405-eng-26

HEALTH PHYSICS DIVISION

EMISSION SPECTRA OF ELECTRON IRRADIATED METAL FOILS

L. C. Emerson, E. T. Arakawa, R. H. Ritchie,
and R. D. Birkhoff

(Submitted by L.C.E. as a thesis to the Graduate Council of
the University of Tennessee in partial fulfillment of the
requirements for the degree of Doctor of Philosophy)

Date Issued

AUG - 9 1963

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the assistance of J. L. Stanford of the University of Tennessee in connection with the preparation of the foils and the determination of their thicknesses. Appreciation is extended to J. C. Ashley for his help in reducing some of the theoretical expressions to tractable forms. D. C. Pittman and J. A. Harter were of assistance in maintaining the accelerator and associated electronic equipment.

This investigation was carried out during the tenure of an Atomic Energy Commission Advanced Health Physics Fellowship administered by the Oak Ridge Institute of Nuclear Studies and held by one of the authors (LCE). The academic phase of this graduate program was completed at the University of Tennessee under the guidance of the staff of the Department of Physics.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
II. PREVIOUS WORK	5
Theoretical	5
Cherenkov Radiation	5
Transition Radiation	7
Plasma Radiation	16
Bremsstrahlung	18
Approach Radiation	21
Experimental	23
III. EXPERIMENTAL APPARATUS	30
Electrical Equipment	30
Electron Gun and Power Supply	30
High Voltage Supply	35
Accelerator	35
Current Measuring Equipment	36
Optical Equipment	37
Spectrometer	37
Polarizer	38
Photomultiplier	38
Auxiliary Equipment	42
Target Chamber	42
Faraday Cup	44
Foil Evaporators	44

CHAPTER	PAGE
Target Assembly	45
Vacuum System	46
IV. AUXILIARY MEASUREMENTS	47
Optical System	47
Spectral Response	47
Calibration Error	52
Wavelength	54
Foil Thickness	55
Interferometric Method	57
Weighing Method	62
Neutron Activation Method	65
Comparison of Methods	67
Optical Constants	68
V. EXPERIMENTAL PROCEDURE	78
Foil Preparation	78
In Vacuum Evaporator	78
In Target Chamber	80
Operation of Accelerator and Spectrometer	83
Data Reduction	86
Correction for Spectrometer Resolution	87
VI. EXPERIMENTAL RESULTS	89
Parallel Polarized Light	89
Perpendicularly Polarized Light	96

CHAPTER	PAGE
VII. COMPARISON WITH THEORY	97
Transition Radiation	100
Spectral Distribution	101
Copper	101
Germanium	107
Silver	107
Tin	115
Antimony	115
Dependence on Electron Energy	119
Dependence on Foil Thickness	123
Bremsstrahlung	131
Spectral Distribution	136
Dependence on Electron Energy	138
Dependence on Foil Thickness	141
Plasma Radiation	144
Cherenkov Radiation	147
VIII. SUMMARY	149
BIBLIOGRAPHY	155
APPENDIX	162

LIST OF TABLES

TABLE	PAGE
I. Intercomparison of the Various Methods of Measuring Foil Thickness	69
II. Metals Evaporated Using Bell Jar Evaporator	81
III. Wavelength, Energy, Thickness, and Polarization Dependence of the Number and Intensity Distribution	98

LIST OF FIGURES

FIGURE	PAGE
1. Pictorial Diagram of Experimental Equipment	31
2. Schematic Diagram of Electron Gun Power Supply	34
3. Schematic Diagram of Modifications to Spectrometer Electric System	39
4. Schematic Diagram of Spectrometer Remote Control Unit	40
5. Schematic Diagram of Wavelength Marker Unit	41
6. Exploded View of Target Chamber and Components Parts	43
7. Arrangement Used in Determining Spectral Response	49
8. Photomultiplier Current Gain as a Function of Applied Voltage	51
9. Spectral Response of Optical System for Light of Both Polarizations	53
10. Diagram of Interferometric Equipment	59
11. Fringe Shift 660-Å Step Photographed with 5461-Å and 4358-Å Mercury Lines	61
12. Real Part of Index of Refraction for Copper	71
13. Imaginary Part of Index of Refraction for Copper	72
14. Optical Constants of Germanium	74
15. Optical Constants of Silver	75
16. Optical Constants of Tin	76
17. Optical Constants of Antimony	77
18. Photon Intensity for 340-Å Tin Foil at 25, 60, and 100 kev ..	91

FIGURE	PAGE
19. Photon Intensity for 690-Å Germanium Foil at 25, 60, and 100 kev	92
20. Photon Intensity for 710-Å Silver Foil at 25, 60, and 100 kev	93
21. Photon Intensity for 1270-Å Copper Foil at 25, 60, and 100 kev	94
22. Photon Intensity for 1600-Å Antimony Foil at 25, 60, and 100 kev	95
23. Theoretical and Experimental Photon Intensity for 1270-Å Copper Foil at 25 kev	102
24. Theoretical and Experimental Photon Intensity for 1270-Å Copper Foil at 60 kev	103
25. Theoretical and Experimental Photon Intensity for 1270-Å Copper Foil at 100 kev	104
26. Theoretical and Experimental Photon Intensity for 690-Å Germanium Foil at 25 kev	108
27. Theoretical and Experimental Photon Intensity for 690-Å Germanium Foil at 60 kev	109
28. Theoretical and Experimental Photon Intensity for 690-Å Germanium Foil at 100 kev	110
29. Theoretical and Experimental Photon Intensity for 710-Å Silver Foil at 25 kev	112
30. Theoretical and Experimental Photon Intensity for 710-Å Silver Foil at 60 kev	113

FIGURE	PAGE
31. Theoretical and Experimental Photon Intensity for 710-Å Silver Foil at 100 kev	114
32. Theoretical and Experimental Photon Intensity for 340-Å Tin Foil at 25 kev	116
33. Theoretical and Experimental Photon Intensity for 340-Å Tin Foil at 60 kev	117
34. Theoretical and Experimental Photon Intensity for 340-Å Tin Foil at 100 kev	118
35. Theoretical and Experimental Photon Intensity for 1600-Å Antimony Foil at 25 kev	120
36. Theoretical and Experimental Photon Intensity for 1600-Å Antimony Foil at 60 kev	121
37. Theoretical and Experimental Photon Intensity for 1600-Å Antimony Foil at 100 kev	122
38. Energy Dependence of Photon Intensity for 1270-Å Copper Foil	124
39. Energy Dependence of Photon Intensity for 690-Å Germanium Foil	125
40. Energy Dependence of Photon Intensity for 710-Å Silver Foil	126
41. Energy Dependence of Photon Intensity for 1270-Å Tin Foil ..	127
42. Energy Dependence of Photon Intensity for 1600-Å Antimony Foil	128

FIGURE	PAGE
43. Thickness Dependence of Photon Intensity for Silver at 60 kev	129
44. Thickness Dependence of Photon Intensity for Silver at 100 kev	130
45. Perpendicular Component of Bremsstrahlung Calculated for a 710-Å Silver Foil at 25 kev	137
46. Bremsstrahlung Intensity for a 1370-Å Tin Foil with Electron Energy of 25 kev	139
47. Bremsstrahlung Intensity for a 1370-Å Tin Foil with Electron Energy of 80 kev	140
48. Energy Dependence of Bremsstrahlung Intensity with an 850-Å Silver Foil at Wavelength of 4300 Å	142
49. Thickness Dependence of Bremsstrahlung Intensity from Silver at Energy of 40 kev and Wavelength of 4300 Å	143

ABSTRACT

An experimental investigation of the visible and ultraviolet light emitted when a charged particle moves across a boundary between two media with different dielectric properties has been carried out. The spectral distributions of the light from evaporated foils of copper, germanium, silver, tin, and antimony bombarded by a 1.5-microamp beam of electrons were measured as a function of electron energy between 25 and 100 keV. The analysis was carried out with a Seya-Namioka vacuum ultraviolet spectrometer, Glan-Foucault prism polarizer, and a quartz window photomultiplier. Calibration of the optical system with a NBS tungsten filament lamp enabled the intensity measurements to be carried out on an absolute basis.

The experimental results for light polarized parallel to the plane containing the photon and the electron were compared with the calculated intensity of transition radiation, and in general the agreement was found to be excellent. The component of the photon intensity polarized perpendicular to this plane was compared with the calculated intensity of the optical portion of the bremsstrahlung spectrum. The predicted dependence on electron energy, photon wavelength, and foil thickness was observed although the measured yield was higher than that predicted by theory. The possibility of contributions from Cherenkov radiation and plasma radiation is also considered, but it is shown that it would have been unlikely for these radiations to have been observed under the experimental conditions of this study.

CHAPTER I

INTRODUCTION

Experimental studies of the light emission from various materials irradiated by electrons predate even the discovery of the electron itself in 1897 by Sir J. J. Thompson. A large part of these studies was directed toward an investigation of the ability of cathode rays to produce luminescence. Not only were these studies concerned with the luminescence of the residual gas within low pressure discharge tubes, but also with that resulting from the direct bombardment of solid materials by the cathode rays.

The investigations were carried out in two general areas, each culminating in a major physical discovery. The first was concerned with an investigation of the properties of the cathode rays themselves and led directly to the discovery of the electron in 1897. The other line of investigation was directed at the effect produced by the rays when they impinged on various materials. These rays, still not identified as electrons, were even passed through thin metallic foils by Hittorf and Lenard in order to study their effects outside the discharge tube. The later repetition of Lenard's experiments led Röntgen to the discovery of X rays in 1895.

This phenomenon of light emission from irradiated solids has been studied for many years with interest being maintained even today. Despite the experimental effort which has gone into the studies, a quantitative understanding of the processes involved has not yet been

achieved for two reasons. First, the light intensity is, in most cases, extremely weak, thus making observations difficult and subject to serious error; and second, the theories which predicted the occurrence of the radiation have, with one exception, been developed only within the past few years. The light which had been observed during irradiation by cathode rays was attributed to "fluorescence",¹ but there was no understanding of the physical processes involved. At various times since then reports have appeared describing light of unknown origin emitted by metal surfaces when subjected to electron irradiation.² In fact, these reports continue even to the present day.³

Following the successful theoretical treatment of Cherenkov radiation by Frank and Tamm⁴ in the late 1930's, the Russian literature, in particular, has contained many papers devoted to the theoretical aspects of a broad class of electromagnetic phenomena produced by the interaction of charged particles with matter. In the last four years experimenters from several countries have begun reporting their studies of optical emission by electron and proton bombardment. The experiments are not easy to carry out, particularly if the results are to be compared with the theories in other than a superficial manner.

¹O. Glasser, Dr. W. C. Röntgen (Springfield: C. C. Thomas, 1958), 2nd Edition.

²J. E. Lilienfeld, *Phys. Z.* 20, 280 (1919); P. D. Foote, W. F. Meggers, and R. L. Chenault, *J. Opt. Soc. Am.* 9, 541 (1924).

³R. M. Chaudhri and M. Y. Khan, *Nature* 192, 647 (1961).

⁴I. Frank and I. G. Tamm, *C. R. Acad. Sci. USSR* 14, 109 (1937).

Since Rudberg's pioneering work in studying the characteristic energy loss spectra of electrons scattered from the surfaces of solid targets,⁵ much attention has been devoted to the theoretical aspects of this problem. In general, two distinct theories have appeared which purport to explain the discrete losses. The first, advanced by Rudberg and Slater in 1936, attributes the losses to interband transitions in which a fixed amount of the electron energy is absorbed by a bound electron within the solid.⁶ The other theory suggests that the energy lost by the primary electron is absorbed in a collective fashion by the free electrons in the material causing an oscillation at a frequency characteristic of the free electron density of the medium.⁷ Both of these theories have had some success in explaining the experimentally observed losses in a variety of materials. It is now clear that both interband transitions and plasma losses must occur, although, in many cases, it is not possible to associate a particular loss with one or the other of the theories. Because of the importance of these theories to the general theory of metals and the contribution to the theories made by experimental studies of the discrete loss spectrum, it would be of some importance to be able to identify particular loss lines as being due to plasma effects or interband transitions. Recently Ferrell⁸

⁵E. Rudberg, Proc. Roy. Soc. (London) A127, 111 (1930).

⁶E. Rudberg and J. C. Slater, Phys. Rev. 50, 150 (1936).

⁷D. Bohm and D. Pines, Phys. Rev. 82, 625 (1951).

⁸R. A. Ferrell, Phys. Rev. 111, 1214 (1958).

has suggested how this may be done. He predicted that plasma oscillations in a metal would decay occasionally by the emission of electromagnetic radiation at the plasma frequency of the metal, and that experimental confirmation of this fact would constitute unequivocal support for the plasma oscillation theory.

It was for the latter reason that this study of the emission spectra of electron bombarded metal foils was initiated. However, during the course of the study other aspects of light emission from metals arose which proved to be of equal interest. It is now clear that the emission spectra cannot be explained on the basis of a single process. While it may be true that each process by which radiation is emitted has a relatively simple explanation in itself, these processes occur simultaneously, and it is their total effect that is observed in the experiments. This compounding has served to make interpretation of the experimental results a difficult task.

CHAPTER II

PREVIOUS WORK

Essentially all of the reported work dealing with the broad topic of light emission from irradiated solids is concerned with materials other than pure metals. There is little doubt that this is largely due to a wide spread belief that pure metals do not fluoresce under irradiation.¹ While it is true that the light emitted from irradiated metals is low in intensity, it does exist and can arise from a number of separate effects.

I. THEORETICAL

There have been many theories which predict that electron-bombarded materials will emit electromagnetic radiation in the visible and ultraviolet region. Although in a specific circumstance these various possible effects may not occur simultaneously, it is necessary to consider each in a general review of the topic.

Cherenkov Radiation

While investigating the luminescence of solutions under irradiation by gamma rays, P. A. Cherenkov,² in 1934, noticed that a weak radiation was emitted from various pure liquids. As a result of

¹H. C. Dake and J. DeMent, Fluorescent Light and Its Applications (New York: Chemical Publishing Company, 1941), p. 185.

²P. A. Cherenkov, C. R. Acad. Sci. USSR 2, 451 (1934).

his subsequent detailed study, he concluded that this was a new phenomena not related to the often observed radiation generally referred to as fluorescence. Frank and Tamm,³ in 1937, on the basis of classical electromagnetic theory, showed that the effect resulted from the polarization of the medium, and later Tamm⁴ provided an expanded and more detailed treatment. This process, which is now well understood, has been extensively studied in the case of transparent media and finds numerous applications in the field of high energy physics.⁵

The basic equation for the Cherenkov radiation yield per unit path length per unit frequency, $\frac{d^2E}{d\omega d\ell}$, is given by

$$\frac{d^2E}{d\omega d\ell} = \frac{e^2}{c^2} \omega \left(1 - \frac{1}{\beta^2 n^2} \right) \quad (1)$$

where e is the electronic charge, c is the velocity of light in a vacuum, ω is the frequency of the radiation, and β is the ratio of the electron velocity to the velocity of light. If the index of refraction, n , is taken to be independent of frequency, Equation (1) may be written on a per unit wavelength basis as

$$\frac{d^2E}{d\lambda d\ell} = \frac{4\pi^2 e^2}{\lambda^3} \left(1 - \frac{1}{\beta^2 n^2} \right). \quad (2)$$

³I. Frank and I. Tamm, C. R. Acad. Sci. USSR 14, 109 (1937).

⁴I. Tamm, J. Phys. USSR 1, 439 (1939).

⁵J. V. Jelley, Cherenkov Radiation and Its Applications (London: Pergamon Press, 1958).

The radiation is emitted at an angle θ with respect to the direction of motion of the charged particle, where θ is given by $\cos \theta = 1/\beta n$. Using this result, Equation (2) may be rewritten to exhibit the angular dependence,

$$\frac{d^2 E}{d\lambda d\ell} = \frac{4\pi^2 e^2}{\lambda^3} \sin^2 \theta. \quad (3)$$

There is symmetry about the direction of motion of the particle and therefore the radiation is emitted along the surface of a cone whose axis coincides with the line of motion of the particle. In practice, the Cherenkov cone has a finite width. This is due to a variety of effects among which are scattering, dispersion, diffraction, and the finite path length of the particle in the medium.

One characteristic of the Cherenkov effect is that the energy of the charged particle must exceed a certain minimum in order for the radiation to occur. For transparent materials the condition is given by $\beta n > 1$, whereas for metals, characterized by a complex dielectric constant ϵ' , it becomes $\beta \sqrt{\text{Re}\epsilon'} > 1$.

Many special cases of Cherenkov radiation have been treated in the literature, but those of concern to this study are discussed along with transition radiation.

Transition Radiation

In a paper published in 1945, Frank and Ginzburg⁶ showed that electromagnetic radiation would be emitted whenever a moving charged

⁶ I. Frank and V. Ginzburg, J. Phys. USSR 9, 353 (1945).

particle passes from one medium to another having different optical properties. Such radiation occurs even though the charge maintains a constant velocity. The case considered by Frank and Ginzburg was that of an electron moving with constant velocity while passing through a plane boundary between a vacuum and a dielectric medium. They treated the problem by representing the field of the moving charge by a system of fixed vertical dipoles located above the boundary between the two media and investigated the radiation field in the far zone by considering the interference of the plane waves from the separate dipoles. A more detailed description of the techniques employed was given in a later publication.⁷ The radiation intensity into a unit solid angle about angle θ (with respect to the surface normal) generated by a single charged particle is given by

$$\frac{d^2 E}{d\lambda d\Omega} = \frac{2\pi e^2 \sqrt{\epsilon'}}{\lambda^4} |A(\theta, \lambda)|^2 \sin^2 \theta, \quad (4)$$

where A is a function which contains the dielectric properties of the material. For a perfect conductor, Equation (4) reduces to

$$\frac{d^2 E}{d\lambda d\Omega} = \frac{2e^2 v^2}{\pi \lambda^2 c^2} \cdot \frac{\sin^2 \theta}{\left(1 - \frac{v^2}{c^2} \cos^2 \theta\right)^2}. \quad (5)$$

⁷ V. L. Ginzburg and I. Frank, J. Exp. Th. Phys. USSR 16, 15 (1946).

In the non-relativistic limit ($\beta \ll 1$) this further reduces to

$$\frac{d^2 E}{d\lambda d\Omega} = \frac{2e^2 v^2}{\pi \lambda^2 c^2} \cdot \sin^2 \theta. \quad (6)$$

Thus, it can be seen that in the case of a perfect conductor the transition radiation reaches a maximum at an angle of $\pi/2$. In the more complete treatment by Frank and Ginzburg, it is shown that for a real metal with non-zero absorptivity the intensity goes to zero at $\pi/2$.

Frank and Ginzburg pointed out that in the special case of a non-relativistic electron moving normally to the boundary surface of a perfect conductor, the radiation emitted is equal to that produced by the annihilation of a dipole located at the boundary surface. This may be seen by integration Equation (6) over the half space to obtain

$$\begin{aligned} \frac{dE}{d\lambda} &= \int_{\Omega} \frac{2e^2 v^2 \sin^2 \theta}{\pi c^2 \lambda^2} d\Omega = \frac{2e^2 v^2}{\pi c^2 \lambda^2} \int_0^{2\pi} \int_0^{\pi/2} \sin^2 \theta \cdot \sin \theta d\theta d\phi \\ &= \frac{8e^2 v^2}{3c^2 \lambda^2}. \end{aligned} \quad (7)$$

Here the θ integration was carried out in only the positive half plane so the limits run only from 0 to $\pi/2$. This result is the same as that derived in Appendix A for the radiation emitted during the sudden collapse of the field of a simple dipole.

Transition radiation and Cherenkov radiation are completely polarized in the plane formed by the path of the incident charged

particle and the direction taken by the emitted photon.

Since Frank and Ginzburg's original paper, there have been many publications dealing with various aspects of the theory. Most of these have not been directly concerned with the particular problem of interest here and will be mentioned only in an effort to secure a rather complete bibliography of the subject.

In his treatment of Cherenkov radiation, Beck⁸ gives an expression for a transition radiation emitted from the surface of a material upon entry by an electron whose velocity is below the Cherenkov threshold. He calculated the theoretical yield and suggested that the radiation would be observable under favorable conditions. However, his treatment did not include dispersive effects which are of importance in any real material.

Klepikov⁹ treated the transition radiation from a semi-infinite medium irradiated by charged particles in a somewhat different fashion than did Frank and Ginzburg and showed that his results agreed with theirs for the radiation in the vacuum. In addition, Klepikov gives an expression for the radiation intensity within the medium for the special case of zero absorption.

The theory of transition radiation was later extended to the case of the charge emerging from a medium into a vacuum¹⁰ under the same

⁸ G. Beck, Phys. Rev. 74, 795 (1948).

⁹ N. P. Klepikov, Moscow Univ. Vestnik 8, 61 (1951).

¹⁰ G. M. Garibian, JETP 6, 1079 (1958).

assumption of zero absorption. In this case Cherenkov radiation also occurs along with the transition radiation. Pafomov¹¹ considered the special cases of the radiation emitted when the charge passed through the boundary between a vacuum and either an isotropic ferrite or a crystal boundary. In addition, he obtained the curious result that under certain conditions the Cherenkov radiation will be emitted at an obtuse angle with respect to the direction of motion of the charged particle. Several theoretical investigations have been carried out for the case of transition radiation from a finite thickness of material. In particular, Pafomov¹² has studied the radiation emitted from a slab in which absorption is taken into account. His results are valid for the radiation intensity in the vacuum region both in the case of the charge entering the slab and the charge leaving the slab. In this case interference phenomena arise due to multiple reflections at the interfaces. Several other papers have dealt with various aspects of the radiation from a finite thickness.^{13,14}

The possibility of enhancing the radiation yield by causing the charged particle to traverse many layers of material, each of which produces a contribution, has been considered by several investigators. Pafomov¹⁴ showed that the radiation intensity from a stack of thin

¹¹V. E. Pafomov, JETP 9, 1321 (1959).

¹²V. E. Pafomov, JETP 6, 829 (1958).

¹³G. M. Garibian and G. A. Chalikian, JETP 8, 894 (1959).

¹⁴V. E. Pafomov, JETP 12, 97 (1961).

plates varies as the square of the number of plates for narrow plate spacing and was proportional to the number for wide spacing. Garibian¹⁵ showed that by varying both the plate thickness and spacing, the radiation could be peaked in either the forward or backward direction. He suggested that transition radiation might be used to measure the energy of an ultrarelativistic particle. For the high energy case the maximum radiation lies in the usual narrow cone at an angle given by mc^2/E . Another treatment of the laminar medium case suggested that it may be possible to use the effect as a generator of power at millimeter and submillimeter wavelengths.¹⁶ Cherenkov radiation may also be enhanced by means of laminar dielectrics as has been pointed out by several authors.^{17,18}

Ginzburg¹⁹ and later Zhelnov²⁰ showed that the charged particle can excite longitudinal oscillations within the medium (plasmons) which can result in the emission of a Cherenkov radiation at a wavelength which is shown to correspond well with the plasma frequency of the medium. This effect, which results from the added consideration of

¹⁵G. M. Garibian, JETP 8, 1003 (1959).

¹⁶R. Pratesi, G. T. di Francia, L. Ronchi, and A. M. Scheggi, Nuovo Cimento 25, 756 (1962).

¹⁷Ia. B. Fainberg and N. A. Khizhniak, JETP 5, 720 (1957).

¹⁸M. L. Ter-Mikaelyan and A. D. Gazazyan, JETP 12, 1183 (1961).

¹⁹V. L. Ginzburg, JETP 6, 1096 (1958).

²⁰B. L. Zhelnov, JETP 13, 117 (1961).

spatial dispersion, is the main contributor to the far zone radiation field in the case of low energy particles ($\beta \ll 1$). It has been pointed out that these treatments neglect absorption, thus in a real material only the radiation produced within several Debye lengths from the surface would escape from the material.²¹

Recently, the theory of transition radiation has been extended to include a study of the far relativistic region. It has been shown that in this case radiation occurs at frequencies greater than the optical frequencies.²²

The most comprehensive treatment of the theory of optical transition radiation has been that of Ritchie and Eldridge.²³ They provided a generalization of the original Frank and Ginzburg theory for a finite foil in which the theoretical dependence of the radiation intensity upon energy, angle, wavelength, and foil thickness is uniquely exhibited. The radiation intensity per incident electron emitted into the unit solid angle about angle θ with respect to the foil normal and per unit wavelength is given by

$$\frac{d^2 E}{d\Omega d\lambda} = \frac{2}{\pi} \cdot \frac{e^2 \beta^2 \mu^2 (1 - \mu^2)}{\lambda^2} \left| \frac{\gamma}{\Delta} \right|^2, \quad (8)$$

²¹R. H. Ritchie, Private Communication.

²²G. M. Garibyan, JETP 10, 372 (1960).

²³R. H. Ritchie and H. B. Eldridge, Phys. Rev. 126, 1935 (1962).

where

$$\begin{aligned} \gamma = & \left\{ \left[\frac{\beta\sigma + \epsilon}{1 - \mu^2\beta^2} - \frac{1}{1 - \beta\sigma} \right] (\mu\epsilon + \sigma) e^{-it\sigma} \right. \\ & + \left[\frac{\beta\sigma - \epsilon}{1 - \mu^2\beta^2} + \frac{1}{1 + \beta\sigma} \right] (\mu\epsilon - \sigma) e^{it\sigma} \\ & \left. - 2\sigma \left[\frac{\epsilon}{1 - \mu\beta} - \frac{1 + \beta\epsilon\mu}{1 - \beta^2\sigma^2} \right] e^{-it/\beta} \right\}, \end{aligned}$$

and $\sigma = (\epsilon - 1 + \mu^2)^{\frac{1}{2}}$, $\beta = v/c$, $\mu = \cos \theta$, $t = 2\pi a/\lambda$, $\Delta = (\mu\epsilon - \sigma)^2 e^{it\sigma} - (\mu\epsilon + \sigma)^2 e^{-it\sigma}$, and a is the foil thickness.

The theory of transition radiation has been extended to include many special cases. The effects of scattering in the ultrarelativistic region have been considered. Garibyan²⁴ showed that in this high energy region multiple scattering leads to modification in the transition radiation intensity in the forward direction at frequencies higher than the plasma frequency ω_p . He attributed the new components to bremsstrahlung. Another treatment of the effects of multiple scattering showed that for high particle energies ($E \gg m_0 c^2$) the transition radiation is enhanced by new frequencies which lie beyond $(E/m_0 c^2)\omega_p$.²⁵ Garibyan and Pomeranchuk²⁶ showed that transition radiation is produced

²⁴G. M. Garibyan, JETP 12, 237 (1961).

²⁵V. E. Pafomov, Acad. Sci. USSR (Proc.) 5, 850 (1960).

²⁶G. M. Garibyan and I. Ya. Pomeranchuk, JETP 10, 1290 (1960).

over a finite path length of the incident particle given by

$$d = \frac{c}{\omega} \left[\left(\frac{m_0 c^2}{E} \right)^2 + \frac{\omega p}{2\omega^2} \right]^{-1} \quad (9)$$

where E is in Mev. For low energy electrons and optical frequencies this reduces to

$$d \cong \frac{2}{\pi} \lambda E^2. \quad (10)$$

Additional extensions to the theory have included the effects of inhomogeneties within the medium,²⁷ diffuse boundaries,²⁸ and, anticipating the practical application of microwave power generation, the production of transition radiation in waveguides.²⁹ Also, Askar'ian³⁰ has proposed a millimeter wave generator based on this effect. Additionally, the production of transition and Cherenkov radiation in a plasma has been considered³¹ as well as their production by electromagnetic waves rather than by charged particles.³²

An interesting account of Cherenkov and transition radiation has been given recently by Frank.³³

²⁷S. P. Kapitza, JETP 12, 954 (1961).

²⁸A. Ts. Amatuni and N. A. Korkhmazyan, JETP 12, 703 (1961).

²⁹K. A. Barsukov, JETP 10, 787 (1960).

³⁰G. A. Askar'ian, JETP 3, 613 (1956).

³¹E. A. Kaner and V. M. Yakovento, JETP 15, 330 (1962).

³²G. A. Askar'yan, JETP 15, 943 (1962).

³³I. M. Frank, Sov. Phys. Uspekhi 14, 740 (1962).

Plasma Radiation

In 1958, Ferrell,³⁴ in considering the plasma oscillations of the conduction electrons in a metal foil, predicted that these oscillations could decay by the emission of electromagnetic radiation at a wavelength characteristic of the plasma frequency of the metal. He shows that this mode of decay is in competition with decay via electronic damping and that for sufficiently short radiation lifetimes the decay via radiation is favored. In the Ferrell theory, the radiation intensity is strongly dependent upon the foil thickness a . This dependency is shown to be related to

$$\frac{2v}{a\omega_p} \sin^2 \frac{a\omega_p}{2v} \quad (11)$$

where ω_p is given in terms of the free electron density, N , by $\left[\frac{4\pi Ne^2}{m} \right]^{\frac{1}{2}}$. This term is a maximum when a is equal to $\frac{1}{2}\lambda_p$ where λ_p is the wavelength corresponding to the plasma frequency. The angular dependence of the radiation is given by

$$I(\theta) = \cos \theta \left[1 + \frac{2c\epsilon_2}{a\omega_p} \cdot \frac{\cos \theta}{\sin^2 \theta} \right]^{-1} \quad (12)$$

where ϵ_2 is the imaginary part of the complex dielectric constant of the metal.

³⁴R. A. Ferrell, Phys. Rev. 111, 1214 (1958).

Several years after the appearance of Ferrell's paper and following several initial attempts to observe the plasma radiation experimentally, Silin and Fetisov³⁵ considered the effect of spatial dispersion on plasma radiation and concluded that in order to observe the effects of this dispersion it would be necessary to use electrons whose kinetic energy was of the order of the Fermi energy of the metal being studied. Actually, Ritchie³⁶ had considered the relation between transition radiation and plasma radiation earlier and had shown that the latter was a special case of the former; e.g., the plasma radiation considered by Ferrell was correctly predicted by and contained within the generalized transition radiation theory. In later publications others reached the same conclusion.^{37,38} To show the equivalence, Ritchie took the limiting case of $\omega/c \ll 1$ and $\epsilon_2 \ll 1$ and chose the real part of the dielectric constant to be that appropriate to a free electron gas in the neighborhood of the plasma frequency, i.e.,

$$\epsilon_1 = 1 - \left(\frac{\omega_p}{\omega} \right)^2. \quad (13)$$

With this modification to his generalized theory he was able to show that the final expression for the radiation intensity reduced to Ferrell's result.

³⁵V. P. Silin and E. P. Fetisov, Phys. Rev. Letters 7, 374 (1961).

³⁶R. H. Ritchie, Am. Phys. Soc. (Bull.) 4, 381 (1959).

³⁷E. A. Stern, Phys. Rev. Letters 8, 7 (1962).

³⁸R. A. Ferrell and E. A. Stern, Am. J. Phys. 30, 810 (1962).

Bremsstrahlung

The process by which a charged particle emits electromagnetic radiation while undergoing acceleration results from its interaction with the field of a nucleus and has long been known.³⁹ The quantum mechanical description was first given by Sommerfeld⁴⁰ and later extended by many writers, perhaps the best known treatment being that by Heitler.⁴¹ Essentially all of the existing work is devoted to the high energy end of the photon spectrum, i.e., the X-ray region; and little attention has been given to the spectral distribution in the ultraviolet wavelength region and beyond. In the few instances in which the bremsstrahlung contribution in the optical region has been considered, the theories of Kramers and Sommerfeld, which are valid at photon energies comparable to the initial energy of the charged particle, have been extrapolated. The validity of such a procedure is somewhat doubtful.

The differential cross section for bremsstrahlung photons and their dependence on polarization has been considered by Gluckstern, Hull, and Breit⁴² for the case of an electron interacting with a single nucleus. In a companion paper this cross section is integrated over the direction of the emerging electron to yield the angular and energy

³⁹A. Kramers, *Phil. Mag.* 46, 836 (1923).

⁴⁰A. Sommerfeld, *Ann. d. Phys.* 11, 257 (1931).

⁴¹W. Heitler, Quantum Theory of Radiation (London: Oxford University Press, 1949), 2nd Edition.

⁴²R. L. Gluckstern, M. H. Hull, and G. Breit, *Phys. Rev.* 90, 1026 (1953).

distribution as well as the polarization of the bremsstrahlung photons.⁴³

The limiting case for $E_{\text{photon}} \rightarrow 0$ is then considered, using a rough estimate of the effect of shielding. The results of their treatment are expressed in the differential cross section for photons of wavelength λ emitted at angle θ with respect to the electron direction and polarized in the plane formed by the directions of the electron and photon:

$$d\sigma_{\parallel} = Z^2 \left[\frac{e^2}{\hbar c} \right] \left[\frac{e^2}{m_o c^2} \right]^2 \frac{(1 - \beta^2)}{\beta^2} \frac{d\lambda}{\lambda} \frac{(\cos \theta - \beta)^2}{(1 - \beta \cos \theta)^4} \sin \theta d\theta$$

$$\times \left\{ \ln \frac{(m_o c^2)^2 \beta^2}{(1 - \beta^2) \left[h^2 \frac{c^2}{\lambda^2} \left(\frac{1 - \beta \cos \theta}{\beta} \right)^2 + \frac{Z^{2/3} (m_o c^2)^2}{(108)^2} \right]} + 0(1) \right\} \quad (14)$$

and for photons polarized perpendicular to this plane:

$$d\sigma_{\perp} = \frac{(1 - \beta \cos \theta)^2}{(\cos \theta - \beta)^2} d\sigma_{\parallel} \quad (15)$$

In the log term, $0(1)$ represents a term of order of magnitude of one. The second term in the denominator of the logarithm predominates for photons in the optical region and the argument reduces to

⁴³R. L. Gluckstern and M. H. Hull, Phys. Rev. 90, 1030 (1953).

$$\frac{(108)^2 \beta^2}{z^{2/3} (1 - \beta^2)} \quad (16)$$

It must be emphasized that the Gluckstern-Hull result was derived on the basis of isolated atoms and consequently does not take into account the modifying effects of the dielectric response of a real scattering medium.

More recently, Ritchie⁴⁴ has considered the low energy bremsstrahlung production in a finite medium by taking account of the dielectric properties of the medium and the presence of boundaries. By assuming single scattering events by the electrons, he shows that the number distribution of the bremsstrahlung photons per electron per unit solid angle and per unit frequency is given by

$$\frac{d^2 N}{d\Omega d\omega} = \frac{\alpha \beta^2 \langle \Theta^2 \rangle \cos^2 \theta}{2\pi^2 \omega} \int_0^a dz_0 \left| \Gamma \right|^2 \quad (17)$$

for photons polarized parallel to the plane of incidence, and

$$\frac{d^2 N}{d\Omega d\omega} = \frac{\alpha \beta^2 \langle \Theta^2 \rangle \cos^2 \theta}{2\pi^2 \omega} \int_0^a dz_0 \left| \frac{(\mu + \sigma) e^{-i\sigma(t-z)} - (\mu - \sigma) e^{i\sigma(t-z)}}{(\mu + \sigma)^2 e^{-i\sigma t} - (\mu - \sigma)^2 e^{i\sigma t}} \right|^2 \quad (18)$$

for photons polarized perpendicular to this plane,

⁴⁴R. H. Ritchie, To be published in J. Math. Phys.

where $z_0 = cz/\omega$,

$$\Gamma = \frac{1}{\left[(\mu - \sigma)^2 e^{it\sigma} - (\mu + \sigma)^2 e^{-it\sigma} \right]} \left\{ \mu \left[(\mu + \sigma) e^{-i\sigma(t-z)} - (\mu - \sigma) e^{i\sigma(t-z)} \right] \right. \\ \left. + \frac{(1 - \mu^2)(\epsilon - 1) \psi}{(\epsilon\mu - \sigma)^2 e^{it\sigma} - (\epsilon\mu + \sigma)^2 e^{-it\sigma}} \right\},$$

$$\psi = \left[(\mu\epsilon + \sigma)(\mu + \sigma)(e^{it\sigma} - e^{-it\sigma}) - 4\mu\sigma e^{it\sigma} \right] e^{-i\sigma(t-z)} \\ + \left[(\mu\epsilon - \sigma)(\mu - \sigma)(e^{-it\sigma} - e^{it\sigma}) + 4\mu\sigma e^{-it\sigma} \right] e^{i\sigma(t-z)}, \quad (19)$$

α = fine structure constant, $e^2/\hbar c$, and $\langle \Theta^2 \rangle$ = the mean square scattering angle per unit thickness. The Ritchie theory does not include relativistic effects and consequently tends to underestimate the photon yield in the forward half plane.

Approach Radiation

The term "approach radiation" is applied to the radiation emitted when a charged particle executes an approach to a surface. It is thus distinguished from the other forms of radiation which are emitted subsequent to the passage of the charge into the medium.

As the charge approaches a conducting surface there is induced on that surface a charge of equal magnitude but of opposite sign. The field of this charge exerts an accelerating force on the incident particle which increases as its distance from the surface decreases.

In his consideration of transition radiation, Klepikov⁴⁵ discussed this aspect of approach radiation and showed that it contributes only a small part of the total radiation emitted. However, in the case of low energy electrons, the incident charge would undergo a greater acceleration and would tend to contribute a larger fraction of the total radiation.

An additional form of approach radiation results if the dipole moment produced by the charge and its image possesses a second time derivative. In special cases this can occur even though the velocity of the incident charge is taken to be constant. Askar'ian⁴⁶ has considered the approach radiation emitted when a charged particle falls upon a spherical conductor, such a system having a finite second time derivative. Bobrinev and Braginskii⁴⁷ show that when a charged particle moving with constant velocity enters a circular hole axially in an infinite conducting plane, the radiation emitted may be thought of as consisting of two parts. The first part is the familiar transition radiation and the second part is a form of approach radiation. The general problem of radiation of charged particles passing near perfect conductors has been treated in the non-relativistic approximation by Dnestrovskii and Kostomarov.⁴⁸ The relativistic problem was considered

⁴⁵N. P. Klepikov, Moscow Univ. Vestnik 8, 61 (1951).

⁴⁶G. A. Askar'ian, JETP 2, 334 (1955).

⁴⁷V. Bobrinev and V. Braginskii, Acad. Sci. USSR (Proc.) 3, 1179 (1958).

⁴⁸Iu. N. Dnestrovskii and D. P. Kostomarov, Acad. Sci. USSR (Proc.) 2, 442 (1957).

in later publications.^{49,50}

II. EXPERIMENTAL

Although the literature (particularly the Russian literature) is voluminous in the theoretical aspects of optical emission from irradiated solids, little experimental work has been reported. Only in the case of Cherenkov radiation has there been much work reported, and this has not included a study of the Cherenkov radiation from metals. As mentioned earlier, in view of the extensive study of cathode rays and their effects, there is little doubt that some of the theoretically predicted effects were observed many years ago. In fact, von Baeyer, as early as 1908, reported that a diffuse radiation was emitted from metal surfaces when interposed in a beam of low energy cathode rays.^{51,52} Whether he was actually observing the effects under discussion is uncertain as several later reports from other workers describe similar experiments but without evidence of radiation.

Although the first theoretical paper on transition radiation appeared in 1945, fourteen years elapsed before any experimental work was undertaken to study the phenomena. There is no question but that

⁴⁹Iu. N. Dnestrovskii and D. P. Kostomarov, Acad. Sci. USSR (Proc.) 4, 132 (1959).

⁵⁰Ibid., p. 158.

⁵¹O. von Baeyer, Phys. Z. 10, 168 (1908).

⁵²Ibid., p. 176.

this radiation had been observed earlier, the first reported detailed observation of the light being that by Lilienfeld⁵³ in 1919. He observed a luminous blue-green spot of light coming from the anode of his X-ray tube when it was struck by a 20- μ a electron beam with an energy of 5 kev. Many of the early observations of the visible radiation were made in connection with the use of X-ray equipment. Vacuums in X-ray tubes were relatively poor by present day standards, and it is possible that gas adsorption on the anode surfaces played some part in the emission of the light that was observed. However, from what is now known regarding this effect, it is certain that transition radiation would have been produced with sufficient intensity to have been observed. Most of the early reports attributed the radiation to some form of luminescence, including bremsstrahlung.⁵³ Others ascribed the radiation to ionization of a gaseous plasma.⁵⁴ Even today the phenomenon is relatively unknown and occasionally a report appears announcing visible or ultraviolet radiation of some unknown origin emitted from an irradiated metal.⁵⁵

⁵³J. E. Lilienfeld, Phys. Z. 20, 280 (1919); P. D. Foote, W. F. Meggers, and R. L. Chenault, J. Opt. Soc. Am. 9, 541 (1924); J. E. Lilienfeld and F. Rother, Phys. Z. 21, 249 (1920); H. Seemann, Phys. Z. 22, 581 (1921); F. Rother and W. M. Cohn, Phys. Z. 31, 687 (1930); W. M. Cohn, Z. Phys. 70, 662 (1931); W. M. Cohn, Z. Phys. 72, 392 (1931); W. M. Cohn, Z. Phys. 73, 662 (1931); W. M. Cohn, Z. Phys. 75, 544 (1932); F. L. Mohler and C. Boeckner, J. Res. NBS 6, 673 (1931); F. L. Mohler and C. Boeckner, J. Res. NBS 7, 751 (1931); F. L. Mohler, J. Res. NBS 8, 357 (1932); C. Boeckner, J. Res. NBS 9, 413 (1932).

⁵⁴K. Sommermeyer, Z. Naturforsch 4a, 440 (1949).

⁵⁵R. M. Chaudhri and M. Y. Khan, Nature 192, 647 (1961).

Goldsmith and Jelley⁵⁶ were the first to attempt a systematic investigation of transition radiation. They irradiated silver, gold, and aluminum with protons of from 1 to 5 Mev energy and measured the light emitted at 86° with respect to the incident beam direction. They reported good agreement with the theory of transition radiation, both with respect to the yield and the polarization. In their interpretation of the Frank and Ginzburg theory of transition radiation they computed the light yield from Equation (6) which holds only for a pure conductor. For such a case the Fresnel coefficient is equal to one, and the transition radiation formula does indeed predict an increase in the radiation as the angle between the electron beam and the direction of observation approaches $\pi/2$. For the real metals used, the dielectric constant, ϵ_2 , is not infinite, and the transition radiation exhibits a dependence on $\cos^2 \theta$. This would indicate that the radiation emitted at their observation angle of 86° with respect to the foil normal and 90° with respect to the proton beam would be very close to zero. Actually, the theory is valid only for normally incident particles, but the 4° angle used in the experiment should not be sufficient to account for the discrepancy. In other respects, particularly for the polarization and the energy dependence, their results seem to agree with theory.

Some support for Ferrell's plasma radiation theory was received

⁵⁶P. Goldsmith and J. V. Jelley, Phil. Mag. 4, 836 (1959).

from the experimental results of Steinmann⁵⁷ and Brown, Wessel, and Trounson⁵⁸ who attained spectral data from thin films of gold and silver. Steinmann studied the relative light yield as a function of foil thickness for silver foils between 450 Å and 1500 Å thick using 25-kev electrons. He concluded that the resulting dependence of yield upon foil thickness was evidence of the validity of Ferrell's theory. Additionally, he found a peak in the light yield at 3300 Å which corresponds to an energy of 3.75 ev. Steinmann's measurements of the energy loss on the same silver foil as used for the irradiation experiments tended to confirm a loss peak between 3.5 and 3.7 ev. Similar experiments with a gold foil showed only a broad continuum in the visible region. Brown, Wessel, and Trounson studied the light emitted from silver foils about 500 Å thick irradiated by 22-kev electrons. They observed a maximum in the angular distribution of the 3300-Å silver peak at about 40° which seemed to confirm Ferrell's theory. Later work by Wessel⁵⁹ also showed that the polarization of the light in the peak agreed with the predictions of Ferrell's theory.

A study of the light emitted from thick foils ($t >$ range of

⁵⁷W. Steinmann, Phys. Rev. Letters 5, 470 (1960); W. Steinmann, Z. Phys. 163, 92 (1961).

⁵⁸R. W. Brown, P. Wessel, and E. P. Trounson, Phys. Rev. Letters 5, 472 (1961).

⁵⁹P. Wessel, Am. Phys. Soc. (Bull.) 6, 310 (1961).

electron) has been reported by Boersch, Radeloff, and Sauerbrey.⁶⁰ They used 6- to 30-kev electrons to study the light emitted at 115° for thick targets of W, Ta, Mo, Ti, Pt, Ag, Cs, Al, Cu, and Ni. They concluded from the angular distribution, spectral distribution, and polarizations that most of the light was due to transition radiation. They also showed that the radiation yield is independent of the target temperature as well as pressure within the irradiation chamber within the range between 10^{-5} and 10^{-9} Torr. It is interesting that an attempt was made over thirty years ago to observe this radiation. Rudberg,⁶¹ reasoning that the discrete energy loss in metals should reappear as radiation, searched for this effect at wavelengths above 2300 Å. The fact that he found nothing was probably due to the low electron energy of 600 ev.

In 1961, Mikhalyak⁶² studied the radiation emitted from thick targets of Al, Ni, and Ag when bombarded by electrons with energies between 6 and 70 kev. At an observation angle of 120° he studied the absolute yield, energy dependence, and polarization for the spectral region covered by the two detectors used (3900 Å and 6500 Å for a photomultiplier which was most sensitive at 4400 Å and 3900 Å to 6600 Å for photographic film where the maximum sensitivity occurred at 6000 Å).

⁶⁰ H. Boersch, C. Radeloff, and G. Sauerbrey, Phys. Rev. Letters 7, 52 (1962); H. Boersch, C. Radeloff, and G. Sauerbrey, Z. Phys. 165, 464 (1961).

⁶¹ E. Rudberg, Proc. Roy. Soc. (London) A129, 652 (1930).

⁶² S. Mikhalyak, "Investigation of Transition Radiation" (unpublished Physical-Mathematical Sciences thesis, M. V. Lomonosov State University, USSR, 1961).

He determined that the energy dependence of the yield followed the theoretical predictions to within 10 per cent to 15 per cent at 60 kev and 30 per cent to 35 per cent at 12 kev. The radiations from Al and Ag were found to be about 90 per cent polarized in the plane of incidence and 70 per cent polarized for Ni. The light was assumed to be composed of transition radiation, optical bremsstrahlung, fluorescence of the cathode and adsorbed gas, and transition radiation with a different plane of polarization produced by scattered electrons. The first absolute measurements of the transition radiation yield from thin targets were made by Frank, Arakawa, and Birkhoff.⁶³ Their experiments were carried out with electron energies up to 100 kev using foils of Al, Ag, and Au of various thicknesses. The photon yields for silver foils with thicknesses between 800 Å and 2400 Å were found to be about 2.5 times those predicted by theory while the yields for aluminum foils with thicknesses between 125 Å and 500 Å were about a factor of 1.5 higher. In addition to absolute yields, studies of the polarization were undertaken. They found that the degree of polarization,

$$P = \frac{E_{||} - E_{\perp}}{E_{||} + E_{\perp}},$$
 was about 0.25 for silver and 0.55 for aluminum, these values being relatively independent of the wavelength. It may be concluded that most of the radiation observed was transition radiation, primarily on the basis of its dependence on the energy and the independence of the foil thickness.

⁶³ A. L. Frank, E. T. Arakawa, and R. D. Birkhoff, Phys. Rev. 126, 1947 (1962).

A continuation of this study was recently reported in which the radiation from several additional metals was investigated.⁶⁴

A form of radiation related to the approach radiation has been observed by Smith and Purcell.⁶⁵ They observed a visible radiation produced by passing a 300-kev electron beam across the surface of a diffraction grating perpendicular to the rulings. The rapid oscillations of the image charge as the beam grazed the surface were thought to be responsible for the observed effect.

Also, the annihilation radiation produced by electron bunches impinging on a surface which had been predicted by Askar'ian has been observed. Hakki and Krumme⁶⁶ produced a power level of 100 milliwatts in the millimeter wavelength region by causing an 800-kev electron beam to impinge on a metal target within a coaxial horn waveguide.

⁶⁴E. T. Arakawa, A. L. Frank, L. C. Emerson, D. C. Hammer, and R. D. Birkhoff, "Optical Emission from Metal Foils Irradiated by High Energy Electrons" (paper presented at the 2nd International Congress of Radiation Research, Harrogate, England, August 5-11, 1962).

⁶⁵S. J. Smith and E. M. Purcell, Phys. Rev. 92, 1069 (1953).

⁶⁶B. W. Hakki and H. J. Krumme, IRE Proc. 49, 1334 (1961).

CHAPTER III

EXPERIMENTAL APPARATUS

The basic equipment may be broadly classified into two groups, electrical and optical. The electrical equipment consisted of an electron gun, electron accelerator, and the power supply and control units necessary to provide a steady beam of electrons at the target location. Also included here is the electronic apparatus used for measuring and recording the low current levels of the electron beam and photon detector. The optical equipment, necessary because of the spectral distribution measurements, consisted of a diffraction grating spectrometer and photomultiplier assembly. Along with these items was the adjunct equipment necessary for the production of the high vacuum as well as the target chamber in which the irradiations were performed. A pictorial diagram of the major pieces of apparatus is shown in Figure 1.

I. ELECTRICAL EQUIPMENT

Electron Gun and Power Supply

Modified versions of the General Electric Company's model 3MP1 electron gun were used to provide a well-focused electron beam at the entrance plate of the accelerator. Modification to the gun consisted of the removal of the electrostatic deflection plates, removal of the heater and cathode assembly, and enlargement of the beam hole in the grid assembly to a diameter of one millimeter. A rectangular hole was cut

UNCLASSIFIED
ORNL-LR-DWG 79279

Figure 1. Pictorial diagram of experimental equipment.

through the side of the grid structure and the filament assembly from a Westinghouse type 1709 lamp was installed with the spiral wound filament adjacent to and directly behind the enlarged hole in the grid assembly. This arrangement obviated the removal of the entire gun assembly from its housing in order to replace a filament. Electron emission from this filament was enhanced by periodic application of a commercially available suspension of rare earth oxides.¹ Bombardment by positive ions, occurring continually during the operation of the accelerator, provided sufficient activation of the cathode.

The gun structure was approximately centered within a brass tube by means of leaf springs mechanically and electrically connected to the second anode. This tube fits into an outer magnetically shielded tube which is bolted to the metal end plate at the entrance to the accelerator. Vacuum seals around the gun assembly are provided by O-rings between the two metal tubes and a glass plate at the rear of the gun structure held against an O-ring by means of a flat lucite plate. The transparent end cover enables an external light beam to be used in the initial alignment of the collimator, target holder, and beam collector. It also provided an opportunity for visual observation of the filament during operation.

Precise positioning of the electron beam was achieved by the adjustment of the two components of a magnetic field normal to the axis of the beam. These fields were provided by adjustable direct currents

¹Obtained from Kulite Tungsten Corporation, Ridgefield, N. J.

carried by two coils surrounding the entire accelerator and spectrometer assembly. Transformer-operated dry rectifiers were used to provide the low voltage current for the coils. The current which supplied the field for the horizontal adjustment was held at a preset steady value by a servo controlled variable transformer in the primary side of the rectifier.

The electron gun power supply was basically that described by Blackstock.² A circuit diagram of the modified gun supply is shown in Figure 2. The noteworthy modifications include a protective circuit breaker which inserts a high resistance between the gun supply and the second anode when the gun emission exceeds 100 μ a. A neon bulb also shorts out the gun emission meter during a high current surge. A fine control of the gun filament voltage was achieved by superimposing a variable AC voltage of ± 0.1 volt on the normal filament voltage of about one volt. This adjustment was used to maintain a constant beam current during the course of an experiment.

To permit operation with the target foil at ground potential, it was necessary to operate the accelerator at negative potentials. This required floating the electron gun power supply at the same negative potential. The necessary insulation was provided by two General Electric type K, 50-kev isolation transformers connected in series.

²A. W. Blackstock, "Discrete Electron Energy Losses in Metallic Foils," ORNL-1910 (June 16, 1955).

Figure 2. Schematic diagram of electron gun power supply.

High Voltage Supply

The power supply used to provide the accelerating potential was a conventional transformer-supplied, full-wave rectifier, model 2120-5 R and D, obtained from the Beta Electric Corporation. The unit provides a continuously variable DC voltage from 0 to 120 kv at currents up to 5 ma. A voltage regulator, Sorensen and Company's model 2000S, was used to provide regulation of ± 0.1 per cent at line voltages from 90 to 130 volts. The high voltage output was filtered by a standard RC type unit, Sorensen and Company's model 2120-5-L2, which provides a ripple of < 0.01 per cent at full rated voltage. The high voltage is applied to the first accelerating electrode via RG-11 coaxial cable. The outer shield of the cable at the output end was flared for a distance of several inches to form a stress cone which was held in place by black electrical tape.

Accelerator

The accelerator proper consisted of a cylindrical tube formed by a series of six accelerating electrodes separated by and cemented to ceramic insulators. The potentials for the electrodes were provided by a string of six 50-megohm, strip-wound carbon resistors across which was applied the full accelerating voltage. The present form of the accelerator is a modification of one which has been previously described.³ The decelerating section was removed and replaced with an

³A. W. Blackstock, R. D. Birkhoff, and M. Slater, Rev. Sci. Instr. 26, 274 (1955).

equivalent length of stainless steel tubing.

The electron gun, accelerator, and the high voltage filter system were installed in a protective wire cage. The control adjustments necessary during operation were made by means of teflon shaft extensions protruding through the wire cage.

Current Measuring Equipment

Output current from the photomultiplier was measured by a model 410 micro-microammeter manufactured by Keithley Instruments, Inc. This instrument, a vacuum tube electrometer, was modified by increasing the value of the capacitors shunting the range resistors to provide some degree of damping of spurious signals, but, at the same time, allowing a response speed consistent with the rate of scan of the spectrum. The resulting time constant was of the order of 0.1 second. The output current was recorded by a standard strip chart recorder. The electron beam current collected after passing through the target was also measured by a Keithly micro-microammeter.

Galvanometers were used to assist in the alignment of the electron beam as well as to monitor the beam current collected by the foil holder. A 1-cm diameter beam collimator was placed at the end of the extension to the accelerator and a galvanometer connected at this point provided a simple method of guiding the beam into the entrance tube of the target chamber. There the beam could be directed through a smaller collimator onto the target by watching for a sudden drop in the current collected by the collimator as the beam was moved across its

surface by varying the current through the field coils.

II. OPTICAL EQUIPMENT

Spectrometer

The light from the metal targets was analyzed by a Jarrell-Ash model 78-650 vacuum scanning spectrometer with a 50-cm focal length. This instrument is of the Seya-Namioka type and has been described previously.⁴ The Seya mounting has the advantage of a relatively wide wavelength range with fixed entrance and exit slit positions. It is ideally suited to investigations of this type because it combines a rapid scanning rate over the spectral region of interest with adequate resolution and transmission. The diffraction grating used was a Bausch and Lomb concave grating ruled with 600 lines per mm and blazed for 3500 Å.

To permit operation of the spectrometer from the control position of the electron gun and accelerator, a remote control system for the spectrometer was constructed. Duplicates of the scanning controls were provided at the remote location as well as a readout of the instantaneous wavelength setting of the diffraction grating. The latter was achieved by a simple servo system composed of a selsyn transmitter coupled to the grating drive and a duplicate selsyn receiver coupled to a Veeder Root counter at the remote position. A schematic diagram of the modifications

⁴A. L. Frank, E. T. Arakawa, R. D. Birkhoff, R. H. Ritchie, and H. B. Eldridge, "Optical Emission from Irradiated Thin Metallic Foils," ORNL-3114 (July 2, 1962).

to the spectrometer control system is shown in Figure 3 while Figure 4 shows the schematic of the remote control unit.

Automatic wavelength calibrations were obtained from a marker pen actuated by a solenoid mounted on the edge of the strip chart on which the photon intensity was recorded. The solenoid was driven by a capacitor discharge which in turn was controlled by a microswitch operated from a cam on the grating drive shaft. A stepping relay was used to reduce the initial signal frequency by a factor of 1, 5, or 10. The schematic diagram of the two components of the marker unit is shown in Figure 5.

Polarizer

After passing through the exit slit of the spectrometer, the light traversed a 26-mm diameter Glan prism⁵ prior to entering the photomultiplier. This prism, used here as an analyzer, is a birefringence polarizer consisting of two calcite prisms separated by an air gap. The useful transmission extends down to about 2200 Å. The prism was mounted in a steel cell fitted into the center of a spur gear which could then be rotated by means of a worm drive mounted on a shaft leading through an O-ring seal to the exterior of the vacuum-tight housing.

Photomultiplier

Measurement of the light intensity of the dispersed spectrum was accomplished by means of a photomultiplier especially selected for low

⁵Obtained from Crystal Optics, Inc., Chicago, Illinois.

UNCLASSIFIED
ORNI-1 R-DWG 79284

Figure 3. Schematic diagram of modifications to spectrometer electric system.

Figure 4. Schematic diagram of spectrometer remote control unit.

UNCLASSIFIED
ORNL-LR-DWG 79283

Figure 5. Schematic diagram of wavelength marker unit.

dark current. The type used, an EMI 6256B, is a 13-stage, quartz window photomultiplier with a 1-cm cesium-antimony photocathode. The spectral response of this tube extends from about 6500 Å down to the quartz cut-off at about 1650 Å. An operating voltage of 1000 volts resulted in a dark current of about 8×10^{-12} amps. Higher voltages increased the gain, but the corresponding increase in dark current resulted in a lower signal to noise ratio. Lower voltages resulted in insufficient gain.

The high voltage for the photomultiplier was supplied by a New Jersey Electronics Corporation power supply, model S-325. This supply is extremely stable, providing a load regulation of 60 mv and a maximum ripple of 5 mv RMS.

III. AUXILIARY EQUIPMENT

Target Chamber

All of the experimental data were obtained using a modified version of an existing fixed-angle brass target chamber. The chamber served as the vacuum-tight union between the exit side of the electron accelerator and the entrance arm of the spectrometer. The other four sides were equipped with O-ring sealed ports and were used to permit access to the interior. An exploded diagram of the target chamber, target assembly, and Faraday cup is shown in Figure 6. The top and bottom ports were used for the target assembly and Faraday cup, respectively. One of the side ports was used as the diffusion pump inlet while the other contained the foil evaporating equipment.

Figure 6. Exploded view of target chamber and components parts.

Electrical connections into the target chamber were made using Kovar seals.

Faraday Cup. The Faraday cup consisted of a 3/4-in. long aluminum cylinder, 1/32 in. thick, and lined on the outside with 0.075 in. of lead. This aluminum liner reduced electron scattering and bremsstrahlung production while the lead shielded out the radiation that was produced by the stopping of the electrons in the cup. The bottom of the cup was inclined at 45° with respect to the direction of the incident electron beam to eliminate the possibility of light from the target reaching the spectrometer through specular reflection from the bottom of the cup.

Foil Evaporators. The evaporator assembly was supported from a teflon plate which also served as the sealing flange on one of the side ports of the target chamber. Five threaded brass rods extended through the teflon plate and were used to support the furnace or filaments and for supplying the electrical power for the heaters. The inside surface of the brass rods was prepared with a sharp annular ridge. When this ridge was drawn up to the plate with nuts turned down on the external portion, it provided the necessary vacuum seal. The use of five such rods permitted four evaporators to be installed for evaporating a series of foils of various thicknesses or for the preparation of different types of foils without necessitating the admission of air to the target chamber.

Two types of furnace assemblies were used. Metals which could be obtained in wire or foil form and which wetted one of the refractory

metals were evaporated from a wire heater. The heater was mounted between two of the support rods and the metal to be evaporated was wrapped tightly around the wire to provide good thermal contact. The other type of heater consisted of a stainless steel tube, 0.100 in. in diameter with a 0.007-in. wall thickness. A small hole (0.040 in.) was drilled into one side of the tube at the center position. This type of heater was used for metals which did not wet the available heater material or for metals which could not be conveniently mounted on a heater wire. These metals were loaded into the tubular heater prior to its mounting between two copper wires which in turn were attached to the supporting rods.

Target Assembly

The target assembly consisted of an aluminum support which held the foil holders at the entrance slit position of the spectrometer. A 1-mm beam collimator hole $\frac{3}{8}$ in. in front of the foil determined the source size and thus the resolution of the spectrometer. The metal target was placed over a $\frac{1}{8}$ -in. hole in a thin stainless steel holder, which later was mounted on the target support by means of a conducting cement. The support was arranged such that two foils could be mounted at one time. Each foil was oriented perpendicular to the other so that when preparing foils within the target chamber it was possible to evaporate a metal on one holder without contaminating the other. A $\frac{3}{16}$ -in. stainless steel rod extending through the lucite cover plate and an O-ring vacuum seal provided both an electrical connection to the

foil as well as a means of adjusting the foil height and orientation.

Vacuum System

Three sets of pumping systems were provided, each consisting of a liquid nitrogen vapor trap followed by a diffusion pump backed by a rotary mechanical pump. The vapor traps were of sufficient size to retain a supply of liquid nitrogen over a 24-hour period. The diffusion pumps used on the accelerator and the spectrometer were the water-cooled type MCF-300 manufactured by the Consolidated Vacuum Corporation. These pumps are of the fractionating variety and, in combination with the cold trap, provided a pumping speed of about 150 liters per second at an inlet pressure of 10^{-6} Torr. A smaller pump, of the same general type but air-cooled, CVC model VMF-21, was used to pump the target chamber directly. The pumping fluid was Dow Corning No. 704 silicone oil. The forepumps were Welch Manufacturing Company "Duo-Seals", model 1397B.

CHAPTER IV

AUXILIARY MEASUREMENTS

The measurement of the absolute light intensity from a metal foil entails a knowledge of the photomultiplier current and electron beam current as well as the optical efficiency of the system for the wavelengths used. The thickness of the metal foils used must also be known if the experimental results are to be compared with theoretical predictions. This comparison also requires that the optical properties of the foils be known for each wavelength at which the comparison is made.

I. OPTICAL SYSTEM

Spectral Response

The overall spectral response of the system is required for the conversion of the photomultiplier current into units of absolute light intensity. In general, the spectral response is determined by the solid angle subtended by the grating at the source, the grating efficiency in the first order, the transmission of the polarizer, and the quantum efficiency and gain of the photomultiplier. An initial attempt at calibration by separate determinations of each of these factors was hampered by a lack of detailed knowledge of quantum yield of the photocathode.

The calibration technique actually employed was based on the measurement of the radiation from a standard lamp of known spectral radiance. The light source used was a General Electric model 30A/T24/7

which had been calibrated against a black body at the National Bureau of Standards. This lamp has a tungsten ribbon filament and a quartz envelope at the exit face. Although the source was calibrated for the wavelength region between 2500 Å and 7000 Å, the falloff in response of the optical system limited the maximum useful wavelength to about 5500 Å. The supplementary optical system, shown in Figure 7, was used to focus a 1:1 image of the tungsten filament on the entrance slit of the spectrometer. For the calibration a circular entrance with a diameter of 0.070 in. was used. The spherical mirror consisted of a grating blank aluminized on the front surface. The normal incidence reflectivity of this mirror and the front surface plane mirror were measured as a function of wavelength using a Beckman model DU spectrometer. The effects of spherical aberration were minimized by keeping the optical path as near as possible to the axis of the spherical mirror.

Since the grating efficiency is different for light polarized in the plane of incidence and that polarized perpendicular to this plane, it was necessary to calibrate the system for each. This was done by measuring the light transmitted by the system with the Glan prism analyzer in the exit arm oriented in each of the two planes of polarization. The incident intensity was taken as one-half of the NBS calibrated value in each of the two mutually perpendicular planes of polarization. As shown by Worthing,¹ the light emitted along the normal

¹A. G. Worthing, J. Opt. Soc. Am. 13, 635 (1936).

UNCLASSIFIED
ORNL-LR-DWG 79287

Figure 7. Arrangement used in determining spectral response.

of a flat tungsten filament is unpolarized.

Since the intensity of the standard lamp was much greater than that of the normal emissions from the targets, it was necessary to operate the photomultiplier at a reduced gain during the calibration procedure. This was accomplished by reducing the voltage across the dynode voltage divider such that the peak output current did not exceed the manufacturer's recommended maximum of $1 \mu\text{a}$ for the tube. The relative current gain, G , of the photomultiplier was measured over a range of voltages and is shown in Figure 8. The gain is independent of photon wavelength.

For a lamp with a radiance of $P_o(\lambda)$ $\mu\text{watts/steradian-mm}^2$ used as shown in Figure 7 and which produces a net photomultiplier current, I_{TL} , the optical efficiency, $E(\lambda)$, of the overall system is given by

$$E(\lambda) = \frac{1}{2} \cdot \frac{P_o(\lambda) \cdot A \cdot R_1(\lambda) \cdot R_2(\lambda)}{I_{TL}} \frac{\mu\text{watts}}{\text{amp-ster-mm}^2} \quad (20)$$

where A is the area of the entrance slit in mm^2 and R_1 and R_2 are the reflectivities of the two front surface mirrors. The factor of $1/2$ is necessary because the polarizer admits only one-half of the total unpolarized intensity for which the lamp has been calibrated.

The photon intensity produced by an electron beam of I_B amps is obtained by multiplying $E(\lambda)$ by the photomultiplier current I_{PM} and, if the result is required on a per electron basis, dividing by the number of electrons passing through the foil per unit time, i.e.,

UNCLASSIFIED
ORNL-LR-DWG 79281

Figure 8. Photomultiplier current gain as a function of applied voltage.

$$\begin{aligned}
 \frac{d^2 E(\lambda)}{d\Omega d\lambda} &= \frac{1}{2} \cdot \frac{P_o(\lambda) \cdot A \cdot R_1(\lambda) \cdot R_2(\lambda)}{I_{TL}} \cdot \frac{I_{PM}}{G} \cdot \frac{1.6 \times 10^{-19}}{I_B} \frac{\mu\text{watts-sec}}{\text{el-ster-m}\mu} \\
 &= \frac{5P_o(\lambda) \cdot A \cdot R_1(\lambda) \cdot R_2(\lambda)}{I_{TL} \cdot G} \cdot \frac{I_{PM}}{I_B} \frac{\text{ev}}{\text{el-ster-cm}} \quad (21)
 \end{aligned}$$

The reciprocal of the quantity multiplying the current ratio I_{PM}/I_B is a measure of the absolute spectral response of the system at wavelength λ . This response for light of both polarizations is shown as a function of wavelength in Figure 9 for a photomultiplier voltage of 10^3 volts. The drop in response in the short wavelength region is primarily due to a reduction in the transmission of the polarizer while that at long wavelengths is due to the combined effects of reduced efficiency of both the grating and the photocathode.

Calibration Error

The calibration procedure as described was performed on four separate occasions. The variations among the results were used to estimate the probable error of the observed spectral response. At a wavelength of 4400 Å, i.e., in the region of maximum response, the probable error of the mean was determined to be 12 per cent. An additional error of 8 per cent was inherent in the original calibration of the tungsten lamp by the National Bureau of Standards. The manufacturer's specifications of 2 per cent error for the ammeter used to measure the current through the standard lamp, 4 per cent error for the

Figure 9. Spectral response of optical system for light of both polarizations.

micro-microammeter used to measure the photomultiplier current, and 5 per cent error for the recorder-voltage divider network were used. The reflectivities of the mirrors used in the calibration were originally measured to within about 2 per cent but because of oxidation and surface wear these values were probably not known to better than about 5 per cent. The gain vs voltage characteristic of the photomultiplier was measured on several occasions and an associated error of about 2 per cent was found. The RMS sum of these errors is 17 per cent and probably represents the minimum overall error associated with the calibration. The calibration errors at the extremes of the wavelength range are certainly larger than this, particularly at the short wavelength end where the scattered light intensity became greater than the intensity of the radiation from the standard lamp.

Wavelength

The wavelength calibration of the spectrometer was obtained by using the line spectrum of a standard mercury lamp centered just outside a 50- μ entrance slit. The spectrum was then scanned slowly and the wavelength setting of the spectrometer was compared with the known wavelength of each of the prominent mercury lines. The calibration thus obtained remained valid until some later adjustment was made in the grating drive system necessitating another comparison with the mercury spectrum.

The sharp lines of the mercury spectrum and the use of narrow slits permitted considerable accuracy in the calibration procedure. With a linear relationship between true wavelength and indicated wavelength

the absolute error throughout the entire range was less than 5 Å. The corresponding error associated with the measurements made during a typical irradiation experiment were probably closer to 10 - 15 Å because of the finite width of the light source and the speed with which the spectrum was scanned.

II. FOIL THICKNESS

The radiation intensity from electron irradiated foils is strongly dependent upon the foil thickness. Especially is this true in the case of transition radiation in the wavelength region of an absorption minimum as interference effects from surface-produced radiation can be expected. For bremsstrahlung the number of scattering centers is determined directly from the foil thickness. Also, the foil thickness has an important role in the absorption of the radiation. For these, as well as other reasons, it is of considerable importance to be able to determine the thickness of each of the foils used in the experiment.

In principle, the foil thickness may be determined by evaporating a known quantity of metal in a known geometrical arrangement. For an evaporation from a plane filament, the resulting deposition pattern is known to follow a cosine law. In the most general case, for plane sources and substrates an evaporation of m grams of metal of density ρ will result in a thickness given by

$$t = \frac{1}{\rho} \cdot \frac{m}{\pi r^2} \cos \theta \cos \phi \quad (22)$$

where θ and ϕ are the angles between normals to the substrate surface and source surface and the line joining the two surfaces, and r is the source to substrate distance.²

In practice, however, it is difficult to realize the calculated thickness because of variations in the evaporation process, the chief difficulties being the incomplete evaporation of the entire mass and the loss of mass via spitting of the molten metal during degassing. As a result, Equation (22) is used only to estimate the mass necessary to produce a specified foil thickness. Generally, several substrate surfaces are mounted above the source, each being at a slightly different distance bracketing the distance calculated to yield the correct thickness. From the series of foils produced in this manner it was usually possible to obtain a foil whose thickness was quite close to the desired value.

For the actual thickness determination one of several methods may be used. The method used here routinely was based on interference phenomena and has been described by Tolansky.³ This method has the dual advantage of requiring a minimum of "technique" in order to use successfully as well as being more rapid than other methods. The other two methods readily available are the neutron activation method and the foil weighing method. Both of these techniques involve a determination of

²L. Holland, Vacuum Deposition of Thin Films (New York: John Wiley and Sons, 1960).

³S. Tolansky, Multiple-Beam Interferometry of Surfaces and Films (London: University of Oxford Press, 1948).

the surface density of the foil which then can be used to determine the thickness if the density of the foil is known. Although it is common practice to assume the bulk density, it is well known that the foil density is smaller for thicknesses less than some critical value. This value varies from metal to metal. One of the problems associated with these methods is that a considerable amount of dexterity is required. It is necessary to remove a precisely measured area from the glass microscope slide and to transfer this fragile piece to an aluminum holder while still intact. As the measuring process results in the destruction of the foil, it is also necessary to remove a second piece from the slide to serve as the target foil.

However, there are inherent advantages to each of these methods which are not possessed by the interferometric method. In particular, the microbalance may be calibrated against a set of standard weights while the activation technique can be used for some metals whose thickness cannot be measured by either of the other two methods, e.g., the alkali metals. With the interferometer it is not necessary to know the foil density; the true metrical thickness is obtained directly. One disadvantage is that, unless special techniques are employed, the thickness of the total deposit (metal plus wetting agent) is determined and not that of the metal alone.

Interferometric Method

This method utilizes the interference pattern produced when a light beam is reflected from two adjacent metal surfaces which are

displaced from one another by a distance equal to the thickness of the film being measured. The displacement of the break in the fringe pattern is then simply related to the height of the step in the surface discontinuity.

In practice, the measurement is made on a piece of the metal remaining on the glass slide immediately adjacent to the section removed for a target foil. An opaque coating of silver is evaporated over the surface of the metal piece and the glass slide. As an evaporated layer accurately contours the surface of the substrate,⁴ this procedure results in a step displacement in the silver coating equal to the film thickness. This surface is then matched against another surface on which a slightly transmitting silver layer has been evaporated. This combination is then illuminated with monochromatic light and the back reflected fringe pattern is observed.

The diagram of the apparatus used is shown in Figure 10. The light source used was a laboratory mercury arc lamp which produced an intense line spectrum. The 5461-Å and the 4358-Å lines used were isolated from the spectrum by means of standard interference filters. The fringe shift was observed with a Leitz Panphot photomicrograph and a Polaroid Land camera. To observe the fringes it was necessary to tilt the slides containing the step because the ring condenser delivers the light to the microscope stage at a slight angle.

Since the fringes are one-half wavelength apart, the thickness

⁴S. Tolansky, Vacuum 2, 231 (1952).

UNCLASSIFIED
ORNL-LR-DWG 79282

Figure 10. Diagram of interferometric equipment.

of the step is given by

$$t = f \cdot \frac{\lambda}{2} \quad (23)$$

where f is the fractional displacement of the fringe shift. In the case of foils whose thickness is near a multiple of a quarter wavelength, there could be an uncertainty in the thickness determination because of the uncertainty in the direction of movement of the fringe shift. This difficulty can be resolved by observing the same fringe pattern using a different mercury line. One of the two possible thicknesses determined with each measurement will be common to both sets and thus is the correct value. Typical fringe patterns for a 660-Å silver foil photographed using the blue and green lines are shown in Figure 11.

The precision with which a particular step may be measured is dependent upon how well the fringe pattern may be focused. The width of a well-focused fringe is about 3 per cent of the spacing; this represents about 80 Å in a typical case. Since it is a relatively simple matter to locate the center line of the fringe to within 10 to 20 per cent, it is possible to determine the thickness of the step to within 10 to 20 Å.

Several possible sources of error inherent in this method have been pointed out.⁵ If the silver overcoat is not completely opaque, then an error can be introduced if the phase change upon reflection from silver deposited on glass differs from that from silver deposited

⁵N. Wainfan, N. J. Scott, and L. G. Parrott, J. Appl. Phys. 30, 1604 (1959).

UNCLASSIFIED
PHOTO 60801

4358 Å Hg LINE

5461 Å Hg LINE

Figure 11. Fringe shift 660-Å step photographed with 5461-Å and 4358-Å mercury lines.

on the metal whose thickness is being determined. Another possibility is that the silver upon striking the metal film during evaporation changes the gross structure of the film making it somewhat thicker and less dense. Also, it is possible that the sticking coefficient for silver on glass and silver on another metal may differ so that the initial rate of deposition of the silver overcoat is different for the two surfaces.

It has also been reported that silver overcoatings used on silver films do not necessarily contour a step accurately and can lead to an underestimate of the film thickness.^{6,7} In the case reported, the error in the metrical thickness amounted to some 25 per cent for silver films about 500 Å thick. The explanation put forth was that the original film is "porous" or discontinuous and fills in more easily with its own metal to form the density of the bulk metal. In fact, it has been shown that silver films even as thin as 50 Å exhibit the bulk density of the metal when the thickness is determined in this fashion.⁸

Weighing Method

This method requires that a known area of the film for which the thickness is desired be accurately weighed with a sensitive micro-balance. The density of the film is then used to determine the thick-

⁶D. G. Avery, *Nature* 163, 916 (1949).

⁷S. Tolansky, Les Propriétés Optiques des Lames Minces Solides (Paris: Centre Nationale de la Recherche Scientifique, 1950).

⁸W. K. Donaldson and A. Khamsavi, *Nature* 159, 228 (1947).

ness. The microbalance used was the Cahn model M-10 electrobalance modified to increase its sensitivity.⁹ The microbalance consists of a lever arm from one end of which is supported the object to be weighed while the other end is rigidly connected to the armature of a torque motor. The object is weighed by measuring the current through the motor which is just sufficient to counterbalance the torque developed by the weight of the object. If some care is exercised in using the balance, it is possible to reproduce readings to within less than 1 μ g.

The balance is calibrated against commercial 1/2-mg, 1-mg, and 2-mg, Class M and Class S weights which are designed to maintain a tolerance within 5 to 15 μ g over several years of service.¹⁰ The reference standards have been in use for a number of years and, as a result of normal wear and oxidation, are probably at the high end of their tolerance range. Although the available calibrating weights were all in the milligram range, Ziemer, Johnson, and Birkhoff¹¹ have shown that the balance is linear in the region below 1 mg.

If W represents the weight of the foil determined with the microbalance, then the thickness is given by $t = W/\rho A$ where ρ and A are

⁹F. Kalil, W. G. Stone, H. H. Hubbell, Jr., and R. D. Birkhoff, "Stopping Power of Thin Aluminum Foils for 12 to 127 kev Electrons," ORNL-2731 (September 3, 1959).

¹⁰National Bureau of Standards, Precision Measurement and Calibration, United States Department of Commerce, Handbook 77, Vol. III (Washington: Government Printing Office, 1961).

¹¹P. L. Ziemer, R. M. Johnson, and R. D. Birkhoff, "Measurement of Stopping Power of Copper by Calorimetric Methods," ORNL-2775 (December 17, 1959).

the density and area of the foil, respectively.

The two main contributions to the overall error are the calibration errors and the error associated with the determination of the foil area. Except for very thin foils which are apt to break apart when removed from the glass slide, the area can be reliably determined to within 5 per cent. The total error associated with an individual measurement is determined to some extent by the thickness and density of the material being weighed as the weighing error is inversely proportional to the mass of the object. Thus, for example, if one assumes the density is the bulk value, the thickness of a 500-Å aluminum foil may be determined to within about 10 per cent, whereas for a 1000-Å gold foil the uncertainty would be only 6 per cent.

There has been agreement among workers in this field that the density of an evaporated film initially is less than the bulk density of the metal and that as the film thickness grows the ratio of the two densities approaches one. However, serious disagreements exist as to the thickness at which the film density becomes equal to the bulk density. For instance, Ishiguro reports¹² that in the case of silver this occurs at a thickness slightly in excess of 100 Å, whereas Blois and Rieser¹³ indicate that the critical thickness is in excess of 1000 Å. Also, in the case of copper, Blois and Rieser report the value to be

¹²K. Ishiguro, J. Phys. Soc. Japan 6, 71 (1951).

¹³M. S. Blois, Jr. and L. M. Rieser, Jr., J. Appl. Phys. 25, 338 (1954).

about 3000 Å while other work indicates the value to be only 300 Å.¹⁴ There is no doubt that the methods by which the measurements were made are at least partially responsible for these discrepancies, but it is also likely that the technique of preparing the foils also plays a part. It is well known that the foil structure can be greatly influenced by such variables as the speed at which the evaporation is carried out, the nature of the-substrate surface, and the residual pressure within the vacuum chamber.

Neutron Activation Method

In many metals the (n,γ) reaction may be used to produce measurable quantities of a radioisotope from extremely small amounts of the parent metal. This is the principle of the so-called activation analysis. This method may be used to advantage to determine the film thickness of any material which has a thermal neutron capture cross section sufficiently large to produce microcurie quantities of activity with available time-integrated neutron fluxes, if the activity so produced has a convenient half life. In addition to serving as a check on other types of thickness measurements, the activation method may be applicable in cases where the other techniques would fail. The method is particularly well suited for thickness measurements of certain of the alkali metals.

¹⁴N. Wainfan, N. J. Scott, and L. G. Parrott, J. Appl. Phys. 30, 1604 (1959).

In essence, the method consists of exposing a foil of known area S to a constant thermal neutron flux ϕ for a time τ . If the microscopic activation cross section is σ_a , then the activity of the foil at a later time T measured from the end of the irradiation period is given by

$$C(\tau, T) = N \sigma_a \phi (1 - e^{-\lambda \tau}) e^{-\lambda T} \quad (24)$$

where N is the number of target atoms in the foil, and λ is the decay constant of the activity produced. By measuring this activity with a radiation counter of known absolute efficiency, the foil thickness t may be determined from the relation,

$$t = \frac{C(\tau, T)}{\sigma_a \phi} \cdot \frac{A}{L \rho S} \cdot \frac{e^{\lambda T}}{1 - e^{-\lambda \tau}} \quad (25)$$

where A is the atomic weight of the foil material, L is Avogadro's number, and ρ is the foil density.

Absolute counting can present a severe problem, and it would be of considerable benefit to be able to determine the thickness without knowing $C(\tau, T)$. The necessity of knowing all of the factors in Equation (25) except S , the foil area, may be eliminated by exposing a standard sample of the same material to the neutron flux along with the foil. If the standard is thin so that the neutron flux is not attenuated appreciably, then the foil thickness is given by

$$t = \frac{M}{\rho S} \cdot R \quad (26)$$

where M is the mass of standard and R is the ratio of the counting rate of the foil to that of the standard. The measurement is greatly simplified because M can be made large enough to be determined accurately and R is merely a ratio which may be measured to a high degree of accuracy using a standard counting system. The dynamic range of most counting systems is sufficiently great to encompass any reasonable set of foil-standard combinations.

Assuming ρ to be known, the three sources of error in this method are those associated with the determination of M , R , and S . In principle, M and R may be reduced to negligible proportions by using a large enough standard and counting for a period of time that will assure good statistics. With very little effort these may be reduced to less than 1 per cent. In measuring thicknesses with the microbalance, the error in measuring the foil area was estimated at 5 per cent primarily because of the necessity of limiting the area of the foil to about 1 cm^2 . This limit in area does not apply here so that the error in measuring S may also be reduced. With care there is no reason why the overall error may not be reduced to 2 to 3 per cent.

Comparison of Methods

The precision with which a typical foil thickness could be measured was determined by preparing a series of copper foils and making repetitive thickness measurements using each of the three available methods. The amount of copper evaporated was 54.6 mg which, according to Equation (22), should have produced foils $512 \text{ \AA}$ thick with the

geometry used. Four microscope slides were mounted adjacent to one another to minimize thickness deviations due to geometrical differences. From the four slides, seven sections were removed for analysis by weighing and four sections for analysis by neutron activation. The copper remaining on the slides was used for a series of ten measurements (several on each of the four slides) using the interferometric method. The results of the measurements are presented in Table I along with the probable error. The probable error in the interferometric method was primarily due to deviations between slides; the deviations in fringe shifts on a single photograph amounted to only $\pm 15 \text{ \AA}$. It is possible that the thickness of the film of wetting agent, which only the interferometric method includes, accounts for the high result in that case.

III. OPTICAL CONSTANTS

The various theories of light emission from metals under bombardment by charged particles all require a knowledge of the optical properties of the metal in order to be properly interpreted. The optical properties are generally expressed in terms of the complex dielectric constant ϵ' which is related in the standard way to the complex index of refraction $\tilde{n}$ by $\epsilon' = \tilde{n}^2$. If $\tilde{n}$ is written as the sum of its real and imaginary parts, i.e., $\tilde{n} = n + ik$, the dielectric constant is given by

$$\begin{aligned}
 \epsilon' &= (n + ik)^2 \\
 &= n^2 - k^2 + i2nk \\
 &= \epsilon_1 + i\epsilon_2 .
 \end{aligned}
 \tag{27}$$

TABLE I
INTERCOMPARISON OF THE VARIOUS METHODS OF MEASURING FOIL THICKNESS

Method	Average Thickness (Å)	Probable Error (Å)
Calculated by Eq. (1)	512	Unknown
Interferometric	574	± 29
Microbalance	558	± 56
Neutron Activation	497	± 26

There is considerable variation in the literature regarding k . It is referred to as the absorption constant, absorption index, or extinction coefficient by different authors. To eliminate any uncertainty as to what is meant by k , it is referred to here as the imaginary part of the complex index of refraction.

The most striking fact regarding the available optical data is the great disparity among the results of different authors. One example, from many available, is that of the real and imaginary parts of the index of refraction of copper which are shown in Figures 12 and 13, respectively.¹⁵ The data from which these figures were drawn were taken from publications extending over a period in excess of 50 years. In addition to an improvement in equipment during this period of time, much was learned about the various factors which influence the optical properties. The literature on these aspects alone is massive. In general, such factors as the method of preparation, rate of deposition, pressure within the system, temperature and quality of the substrate surface, and thickness of the final product are known to be of importance in such studies. In view of this it is not surprising that differences exist among the results of different workers.

While the uncertainty regarding the optical constants does not affect the accuracy of the experimental results of this investigation,

¹⁵R. S. Minor, Ann. d. Phys. 10, 581 (1903); J. T. Tate, Phys. Rev. 34, 321 (1912); G. Pfestorf, Ann. d. Phys. 81, 906 (1926); J. Malsch, Ann. d. Phys. 7, 360 (1930); L. G. Schulz, J. Opt. Soc. Am. 44, 357 (1954); L. G. Schulz and F. R. Tangerlini, J. Opt. Soc. Am. 44, 362 (1954).

Figure 12. Real part of index of refraction for copper.

UNCLASSIFIED
ORNL-LR-DWG 79308

Figure 13. Imaginary part of index of refraction for copper.

it does make a comparison between the results and theoretical predictions more uncertain. For this reason, several sets of data were used, when available, in the correlation between experimental and theoretical results.

The optical constants for germanium were obtained from the work of Archer and Rustgi, Nodvik, and Weissler¹⁶ and are shown in Figure 14. The unusual optical properties of silver have been responsible for a considerable effort on the part of many workers in connection with the experimental determination of n and k . However, the extremely careful work of Philipp and co-workers has probably resulted in their values being the most accurate of those available. Tabular data for n and k were supplied by Taft¹⁷ from recent work by Ehrenreich and Philipp¹⁸ and are shown in Figure 15. The optical data for tin, shown in Figure 16, were obtained from the work of Quincke and Erochin,¹⁹ while the data for antimony were obtained from Quincke, Hass, Chatterjee and Prasad²⁰ and are shown in Figure 17.

¹⁶R. J. Archer, Phys. Rev. 110, 354 (1958); Om. P. Rustgi, J. S. Nodvik, and G. L. Weissler, Phys. Rev. 122, 1131 (1961).

¹⁷These data were kindly supplied prior to their publication by E. A. Taft.

¹⁸H. Ehrenreich and H. R. Philipp, Phys. Rev. 128, 1622 (1962).

¹⁹G. Quincke, Ann. d. Phys. 23, 142 (1884); P. Erochin, Ann. d. Phys. 39, 213 (1912).

²⁰G. Quincke, Ann. d. Phys. 23, 142 (1884); G. Hass, Ann. d. Phys. 31, 245 (1938); L. M. Chatterjee and K. N. Prasad, Current Sci. 13, 177 (1944).

UNCLASSIFIED
ORNL-LR-DWG 79311

Figure 14. Optical constants of germanium.

UNCLASSIFIED
ORNL-LR-DWG 79309

Figure 15. Optical constants of silver.

UNCLASSIFIED
ORNL-LR-DWG 79310

Figure 16. Optical constants of tin.

Figure 17. Optical constants of antimony.

CHAPTER V

EXPERIMENTAL PROCEDURE

The procedures followed in obtaining the spectral distribution of the light emitted by the foil under electron bombardment are associated primarily with the preparation and mounting of the metal foil and the operation of the accelerator and spectrometer during the irradiation.

I. FOIL PREPARATION

The metallic foils used in the course of the experiment were prepared by vacuum evaporation techniques. The targets were either prepared in a vacuum bell jar and mounted at atmospheric pressure before being installed in the target chamber, or they were evaporated directly on the foil holder within the target chamber using the equipment described in Chapter III. In the latter case it was possible to obtain the experimental data without exposing the freshly prepared target to the atmosphere. However, this required the use of a thin transparent substrate on which the metal was evaporated.

In Vacuum Evaporator

In the case of foils prepared externally the equipment consisted of a standard 15-in. diameter bell jar containing an electrically heated evaporator. The pumping system consisted of a Consolidated Vacuum Corporation MCF-300 oil diffusion pump backed by a Welch Duo-Seal 1397B

mechanical pump. Typical evaporating pressures ranged from 1×10^{-6} Torr to 2×10^{-5} Torr. The evaporator assembly was provided with three high current terminals which allowed two separate evaporations to be made during the course of one operating cycle. Alternating currents up to 300 amps could be obtained from a low voltage supply consisting of a 2-KVA transformer with an 8-volt secondary. The current was controlled by a variable auto-transformer wired in the primary side of the step-down transformer. In addition, a solenoid operated shutter was contained within the system to shield the condensing element from evaporator impurities which are released during the initial outgassing procedures.

Glass microscope slides were used as the condensing elements. Several slides were arranged at varying distances from the electrical heaters in order that a series of foils of varying thicknesses could be obtained by a single evaporation. The use of glass here rather than some opaque material had the advantage of providing a variable density filter through which the heater could be observed during evaporation.

The availability of separate heaters permitted the use of one for the evaporation of the metal and the other for the evaporation of a wetting agent on the condensing plates. The wetting agents used were sodium phosphate (meta) and a commercial agent, Victowet.¹ The evaporated foil was removed from the glass slide by carefully immersing the edge of the slide in water, dissolving the wetting agent, and allowing surface tension to gradually peel the foil from its backing.

¹Victowet 35B, obtained from Victor Chemical Works, Chicago, Ill.

Following this operation the foil was picked up on the standard rectangular foil holder shown in Figure 6 with the foil covering the central 1/8-in. diameter hole. This technique of preparation provided a smooth foil surface and had the additional advantage that no backing material was necessary. Foils of essentially any thickness down to about 300 Å were prepared in this manner.

The types of metals evaporated using the bell jar evaporator along with the details of the heaters used are shown in Table II. In general, the recommendations of Holland² were followed.

The glass slide containing the remaining metal was then remounted in the evaporator and a layer of silver was evaporated covering the edge as required for the interferometric thickness determination. When a section of the foil was needed for weighing, an additional piece was removed at the same time as the section serving as the target.

The foils prepared and mounted in this manner were stored in a vacuum desicator if they were not to be installed immediately in the target chamber. Foils stored in the desicator showed no apparent change with time either in their physical appearance or in their emission spectra.

In Target Chamber

Antimony foils were prepared directly in the target chamber itself with the target holder also serving as the support for the

²L. Holland, Vacuum Deposition of Thin Films (New York: John Wiley and Sons, 1960).

TABLE II
METALS EVAPORATED USING BELL JAR EVAPORATOR

Metal	Melting Point (°C)	Evaporator Material
Copper	1083	Tantalum
Germanium	959	Tantalum
Silver	961	Molybdenum
Tin	232	Tantalum

condensing surface. With this arrangement, it was impossible to obtain the emission spectra from the unsupported foil but only from the foil mounted on the transparent substrate. The main advantage of this technique is that the freshly prepared surface was not exposed to the atmosphere prior to the study of its emission spectra.

Formvar was used as the backing material.³ The backings were prepared by floating a drop of a 1-per cent solution of Formvar in dichloroethane on a clean water surface and picking up the floating film on a metal plate provided with a 1-in. hole. The Formvar was carried upward by raising the plate vertically through the floating film which resulted in a double layer being formed over the hole. This double layer was then transferred to the foil support plate and the latter mounted in position on the front of the target holder.

Just prior to irradiation the antimony was evaporated to form a metallic film on the surface of the Formvar. A 20-gauge Chromel wire was used as the heater with the antimony source wrapped around the wire so as to make good thermal contact. This heater was then installed on the electrical binding posts shown in Figure 6 and the entire unit mounted in the side port of the target chamber. With the target holder in position the evaporator-foil distance was 6.1 cm. Following evacuation of the target chamber to the operating pressure of about 5×10^{-6} Torr, the filament heater was gradually brought up to the melting temperature of antimony with the target holder rotated to a position

³Obtained from the Shawinigan Products Corp., New York, N. Y.

such that the surface of the Formvar was not exposed to the heater. This prevented the coating of the Formvar by contaminants released during the outgassing of the heater and antimony source. After the antimony had melted, the target holder was rotated back to the normal evaporation position so that the Formvar faced the heater and then the heater temperature was raised until a visible coating of antimony covered the foil holder. The holder was then rotated 90° back to the operating position and the emission spectrum measurements were initiated within a period of several minutes.

The film thickness was determined interferometrically by removing a portion of the foil still mounted on the Formvar subsequent to the experiment. In this case it was necessary to subtract the thickness of the Formvar backing from the total thickness in order to obtain the thickness of the antimony film. A series of interferometric measurements of thicknesses of typical backings yielded an average value of 350 Å. The two- to three-hundred angstrom spread in the thicknesses determined in this manner resulted in probable errors in film thicknesses which were much greater than those found for the foils evaporated directly onto glass slides.

II. OPERATION OF ACCELERATOR AND SPECTROMETER

An extensive system of valves provided a means of isolating each cold trap, diffusion pump, and forepump combination as well as each major component of the accelerator-spectrometer system. These valves permitted continuous operation of the pumping systems except for extended

shutdown periods. In addition, when exposure of one part of the system to atmospheric pressure was necessary, the valving arrangement was used to retain the high vacuum in other parts of the system. Operations requiring the admission of air to the system were normally those associated with changing the target and recoating the filament in the electron gun. Air admitted to the system was always passed through a calcium chloride drying column to remove most of the moisture.

Whenever the target chamber was opened, it was customary to rotate the diffraction grating to prevent stray light from reaching the photomultiplier and possibly damaging the photocathode surface. This procedure resulted in reduced dark currents since it permitted the constant application of the photomultiplier voltage.

The last operation prior to evacuation of the complete system was the installation of the target assembly and, when required, the internal evaporator assembly. The valving system permitted the spectrometer forepump to be used as a roughing pump for the system. This valve was initially throttled down to prevent the foil or Formvar substrate from being ruptured by air currents within the target chamber. When the pressure was reduced to 1 to 10 mm Hg, the valve was opened fully and pumping continued until the pressure dropped to about 100 microns at which time the diffusion pumps were opened to the system.

Within 10 to 15 minutes the pressure dropped to 1 to 2×10^{-6} Torr in the accelerator tube and to about 5×10^{-5} Torr in the target chamber. While it was possible to operate the accelerator at this pressure, it was generally desirable to wait until the pressure leveled

off to about 6 to 7×10^{-7} Torr in the accelerator and 5 to 6×10^{-6} in the target chamber. This required a period of several hours.

The internal preparation of the target foil was not carried out until everything was ready for the experiment. This was delayed purposely to minimize oxidation of the metal surface. It was possible to reduce the time lag between evaporation and experiment even further by adjusting the electron beam to strike the back of the foil holder and then temporarily decreasing the beam current during the evaporation period. The time lag with such a procedure was of the order of one minute.

The adjustment of the electron beam was simply a matter of varying the accelerating and focusing voltages on the electron gun while directing the electron beam into the Faraday cup by use of the two field coils. It was possible to obtain a well-focused beam for energies between 40 and 80 kev, but outside of this range the beam was rather poorly focused due to a lack of available range of voltages from the electron gun supply. When properly focused it was possible to pass over 90 per cent of the beam through a 0.040-in. diameter hole located about 5 feet from the exit end of the electron gun.

In general, the beam current in the Faraday cup was maintained at $1.5 \mu\text{a}$. This provided sufficient light yield while at the same time did not heat the target appreciably. The light output with such a current was easily visible to the dark-adapted eye. The spectrum was scanned from $2000 \text{ \AA}$ to $6000 \text{ \AA}$ with the short wavelength limit being dictated by the polarizer transmission and the long wavelength limit

by the sensitivity of the photocathode. Three separate runs were usually made at each energy, two with the polarizer set to transmit light polarized parallel to the plane of incidence and one with the polarizer set for the perpendicular component.

To eliminate backlash effects, the spectrum was always scanned in the same direction. The spectrum was generally scanned at a speed of 1000 Å per minute. The high energy data were always obtained first since this tended to minimize any possible effects of foil heating.

Data Reduction

Where more than one run was made on a single spectrum, the strip recorder chart paper was cut apart and superimposed so that a single best fitting line could be drawn to represent the data. The photomultiplier current was then read from this curve at 100-Å intervals in the spectral region between 2500 Å and 5500 Å. The dark current was subtracted from each value and the resulting net current was used in Equation (21) to obtain the photon intensity distribution as a function of wavelength.

This computation was programmed for the IBM-7090 and the CDC-1604-A digital computers because of the voluminous amount of experimental data. The computers, in addition to furnishing a listing of the photon intensities, also wrote the data on magnetic tape which was then used by a Cal-Comp-570 plotter to furnish a graph of each separate run. This relatively inexpensive procedure facilitated the subsequent comparison of these data with the theoretical predictions.

Correction for Spectrometer Resolution

The features of a sharp spectral line are modified by the finite resolution of the spectrometer. For example, the measured intensity of a discrete spectral line is lower than the actual intensity if the width of the line is less than the resolution of the spectrometer. Thus, to compare theoretical predictions with experimental results, it is necessary to take this modifying effect into account. It would be more desirable to correct the experimental results, but, as this is difficult to accomplish, the corrections are applied to the theoretical values.

If the calculated intensity at wavelength λ is denoted by $I(\lambda)$ then the intensity which should be compared with the experimentally measured intensity is given by

$$I_M(\lambda) = \frac{\int_0^{\infty} I(\lambda') f(|\lambda' - \lambda|) d\lambda'}{\int_0^{\infty} f(|\lambda' - \lambda|) d\lambda'} \quad (28)$$

where $f(\lambda' - \lambda)$ is the fraction of $I(\lambda')$ that is passed by the spectrometer when the grating is set at wavelength λ . Because of the symmetry of the pass band it is customary to replace f by the unit step function. The width of the step function is adjusted such that the integral over the step is equivalent to the integral over the pass band of the spectrometer. In this case Equation (28) becomes

$$I_M(\lambda) = \frac{\int_0^{\infty} I(\lambda') \left[S(\lambda' - \lambda + \epsilon) - S(\lambda' - \lambda - \epsilon) \right] d\lambda'}{\int_0^{\infty} \left[S(\lambda' - \lambda + \epsilon) - S(\lambda' - \lambda - \epsilon) \right] d\lambda'}$$

$$= \frac{1}{2\epsilon} \int_{\lambda-\epsilon}^{\lambda+\epsilon} I(\lambda') d\lambda'. \quad (29)$$

With ϵ taken to be the half-width of the central image measured at half the maximum height, the deviation between the area of the central image and a unit step with a width of 2ϵ was found to be less than 5 per cent.

When the theoretical spectrum was such as to necessitate the application of this correction the measured value for ϵ of $19 \text{ \AA}$ was used.

CHAPTER VI

EXPERIMENTAL RESULTS

The light emitted by irradiated foils of copper, germanium, silver, tin, and antimony was studied as a function of wavelength and its dependence on the electron energy. In the case of silver the dependence of the intensity upon the foil thickness was also determined. The intensity of the light emitted by each of the foils studied was measured both for its component polarized parallel to the plane of incidence and that perpendicular to this plane. All of the data were obtained with an angle of 30° between the direction of photon emission and the direction of the electron beam.

Although these results are to be compared with theory in the next chapter, there is some advantage to be gained in presenting all of the experimental data for one foil in a single figure. In this way it is possible to recognize certain features which may be characteristic of the experiment.

1. PARALLEL POLARIZED LIGHT

Except at the extremes of the scanned spectral regions the photon intensity was sufficient to produce photomultiplier currents considerably larger than the background of dark current. This enabled the intensity to be measured over the wavelength region of interest with a minimum of error. As mentioned previously, the calibration errors are larger at the extremes of the spectral region scanned, and, for this

reason, the validity of the results there are questionable.

With the exception of the silver spectrum the general appearance of the wavelength dependence of the photon intensity for all of the metals is similar. The typical spectrum is characterized by a fairly rapid drop in intensity out to about 3500 Å followed by a more gradual decline throughout the remainder of the region investigated. The spectrum of silver has, in addition to these general features, a relatively sharp and intense peak at a wavelength of about 3325 Å. The measured photon intensities, in absolute units, are shown for each metal investigated in Figures 18 through 22. Although additional results were obtained also for 40 and 80 kev, these curves are omitted as their general features are the same as those shown. For each metal these omitted data lie in the region between 25 and 60 kev and 60 and 100 kev, respectively.

The drop in intensity at 2500 Å and the slight rise between 5200 and 5500 Å probably reflects the calibration errors mentioned earlier. The small hump seen in most of the figures in the region between 3000 and 3500 Å and again near 4900 Å is probably not statistical in origin. Although the deviations of these characteristics from a smooth curve are less than the relative error of the calibration, the fact that they appear so regularly suggests that random errors cannot be responsible. While the origin of these humps is unknown, it is obvious that it is not characteristic of the metal being irradiated. It is possible that they may be due to the slight irregularities in the response of the grating.

UNCLASSIFIED
ORNL-LR-DWG 79289

Figure 18. Photon intensity for 340- $\text{\AA}$ tin foil at 25, 60, and 100 keV.

UNCLASSIFIED
ORNL-LR-DWG 79290

Figure 19. Photon intensity for 690- $\text{\AA}$ germanium foil at 25, 60, and 100 kev.

Figure 20. Photon intensity for 710- $\text{\AA}$ silver foil at 25, 60, and 100 kev.

UNCLASSIFIED
ORNL-LR-DWG 79292

Figure 21. Photon intensity for 1270-Å copper foil at 25, 60, and 100 kev.

UNCLASSIFIED
ORNL-LR-DWG 79293

Figure 22. Photon intensity for 1600- $\text{\AA}$ antimony foil at 25, 60, and 100 kev.

The existence of such irregularities has been recently demonstrated.¹

II. PERPENDICULARLY POLARIZED LIGHT

In comparison with the photon intensity of the parallel polarized component, the intensity of the perpendicularly polarized component is negligible except for low electron energies. In most cases the net photomultiplier current due to the foil emission is less than the typical dark current of 9 μa . With this situation the determination of the photon intensity is, at best, marginal. Interpretation of the spectra is made even more difficult by the random fluctuations of the recorded current which, although small, are a significant fraction of the average.

The experimental results for several of the metals are presented in connection with the discussion of bremsstrahlung.

¹D. C. Hammer, E. T. Arakawa, and R. D. Birkhoff, To be published in Appl. Optics.

CHAPTER VII

COMPARISON WITH THEORY

The light intensity emitted by the foils includes contributions from a number of separate effects. A comparison of the experimental results with the predictions of the various theories is of value in determining the contribution of each of these to the measured photon intensity.

Different authors express their results in terms of various distribution functions which may exhibit a different dependence upon wavelength. Two broad classes of distributions are used: the photon number distribution and the photon intensity distribution. A further distinction expresses either distribution on a per unit frequency basis or on a per unit wavelength basis. The various commonly used distributions, with their dependence upon wavelength, energy, and thickness are shown in Table III for the different types of radiation. Here it is assumed that the real and imaginary parts of the index of refraction, n and k , are independent of wavelength. For reasons of uniformity, all discussions of light emission are based on the photon intensity in units of electron volts per incident electron per unit solid angle per unit wavelength.

Bremsstrahlung may be distinguished from the other radiations which may be present by the identification of a perpendicularly polarized component in the experimental results. This assumes that only the four processes listed in Table III contribute to the measured

TABLE III

WAVELENGTH, ENERGY, THICKNESS, AND POLARIZATION DEPENDENCE
OF THE NUMBER AND INTENSITY DISTRIBUTIONS

Radiation	Quantity	Wave-length	Energy	Thickness	Polarization
Cherenkov Radiation	$\frac{d^2 N}{d\ell d\omega}$	Constant	Has a threshold at	Finite thickness reduces intensity and increases width of the Cherenkov cone.	Parallel
	$\frac{d^2 N}{d\ell d\lambda}$	$\frac{1}{\lambda^2}$	$E = m_0 c^2 \times [(1-n^2)^{\frac{1}{2}} - 1]$		
	$\frac{d^2 E}{d\ell d\omega}$	$\frac{1}{\lambda}$	Higher energy increases angle of emission.		
	$\frac{d^2 E}{d\ell d\lambda}$	$\frac{1}{\lambda^3}$			
Transition Radiation	$\frac{d^2 N}{d\Omega d\omega}$	λ	E	Oscillatory with period of	Parallel
	$\frac{d^2 N}{d\Omega d\lambda}$	$\frac{1}{\lambda}$		$\beta \cdot \frac{\lambda}{2}$	
	$\frac{d^2 E}{d\Omega d\omega}$	Constant		for $\epsilon_2 \ll 1$	
	$\frac{d^2 E}{d\Omega d\lambda}$	$\frac{1}{\lambda^2}$		and small t.	

TABLE III (continued)

Radiation	Quantity	Wave-length	Energy	Thickness	Polarization
Bremsstrahlung	$\frac{d^2 N}{d\Omega d\omega}$	λ	$\frac{1}{E}$	t (in the limit of small t)	Parallel and Perpendicular
	$\frac{d^2 N}{d\Omega d\lambda}$	$\frac{1}{\lambda}$			
	$\frac{d^2 E}{d\Omega d\omega}$	Constant			
	$\frac{d^2 E}{d\Omega d\lambda}$	$\frac{1}{\lambda^2}$			
Plasma Radiation	$\frac{d^2 N}{d\Omega d\omega}$	Predicts radiation only at λ_p .	E	Oscillatory with period of $\beta \cdot \frac{\lambda_p}{2}$.	Parallel
	$\frac{d^2 N}{d\Omega d\lambda}$				
	$\frac{d^2 E}{d\Omega d\omega}$				
	$\frac{d^2 E}{d\Omega d\lambda}$				

intensity. Plasma radiation can be identified by the presence of a relatively sharp peak in the photon intensity occurring at a wavelength characteristic of the plasma frequency. Experimental verification of Cherenkov radiation is made difficult by the necessity of using foils of finite thickness which, in addition to spreading out the peak and reducing its intensity, also results in a strong background of transition radiation. In the special case of a thick transparent non-metal, the imaginary part of the dielectric constant is small, and the Cherenkov radiation appears as a relatively sharp peak at an angle given by $\theta = \cos^{-1} \frac{1}{\beta n}$. Transition radiation can be distinguished from the parallel polarized component of bremsstrahlung by its quite different energy dependence.

Except in rare instances, Cherenkov radiation cannot be uniquely identified in experiments of this type. In view of this fact, and also because of the absence of plasma radiation except at the characteristic wavelength, the major contributions to the measured radiation intensity are expected to be due to transition radiation and bremsstrahlung. For this reason, the comparisons between theory and experiment are made by identifying the parallel polarized component of the radiation as primarily transition radiation and the perpendicular polarized component as bremsstrahlung.

1. TRANSITION RADIATION

The intensity of transition radiation was computed from Equation (8) using the values of the optical constants obtained from the curves

in Chapter IV. All of the calculations were performed on a Control Data Corporation model 1604-A digital computer.¹ Equation (8) shows the photon intensity as a function of wavelength, electron energy, foil thickness, and angle of photon emission. Of these parameters, only the angle was held constant throughout the course of the experiment. The machine calculation was performed for each combination of the three remaining parameters characterizing one of the experimentally studied cases.

Spectral Distribution

The parameter most easily varied was the wavelength as it involved only a rotation of the grating. Consequently, the spectral distribution of the photon intensity was obtained for several beam energies for each foil thickness studied.

Copper. Experimental data were obtained for three copper foils with thicknesses of 710 Å, 840 Å, and 1270 Å at five energies between 25 and 100 kev. As the general features of the spectral distributions are not appreciably altered by foil thickness, only the data obtained for the 1270-Å foil are presented. Figures 23, 24, and 25 show the absolute experimental and theoretical photon intensities as a function of wavelength for electron energies of 25, 60, and 100 kev, respectively. The theoretical intensity was calculated from Equation (8) using the

¹The complex arithmetic subroutines used in the computer program were modified versions of those written earlier by H. B. Eldridge for the IBM-7090 computer.

UNCLASSIFIED
ORNL-LR-DWG 79295

Figure 23. Theoretical and experimental photon intensity for 1270- $\text{\AA}$ copper foil at 25 kev.

Figure 24. Theoretical and experimental photon intensity for 1270- $\text{\AA}$ copper foil at 60 kev.

UNCLASSIFIED
ORNL-LR-DWG 79297

Figure 25. Theoretical and experimental photon intensity for 1270-Å copper foil at 100 kev.

appropriate optical constants for copper.² The general shape of the experimental curve follows that of Ritchie's generalized theory of transition radiation, but the magnitude is higher than the theoretical predictions by a factor of 2 or 3 at 25 kev. This disagreement is not as pronounced at 60 kev while at 100 kev it is less than the estimated probable error in the experimental results. There are several possible explanations why the data do not agree at lower energies. First, by neglecting the contribution of the parallel polarized component of bremsstrahlung, the theoretically predicted photon intensity is underestimated. Because of the $1/E$ dependence of bremsstrahlung the error is greater at the lower energies. A second explanation is associated with the scattering of the electron beam by the foil. Scattering is more predominant at low energies, as the RMS scattering angle varies approximately as $1/E$,³ and, if responsible for the discrepancy, would give rise to larger deviations between theory and experiment at low energies. Scattered electrons which miss the Faraday cup cause more radiation than predicted for two reasons. First, these electrons are stopped somewhere in the system and give rise to radiation at that point. This radiation, if seen by the grating, results in an increase of the measured photon intensity. The second reason is that if the

²R. S. Minor, Ann. d. Phys. 10, 581 (1903); J. Malsch, Ann. d. Phys. 7, 360 (1930); L. G. Schulz, J. Opt. Soc. Am. 44, 357 (1954); L. G. Schulz and F. R. Tangerlini, J. Opt. Soc. Am. 44, 362 (1954).

³E. J. Williams, Proc. Roy. Soc. (London) A169, 531 (1939); Phys. Rev. 58, 292 (1940).

scattered electrons miss the Faraday cup then the measured beam current is smaller than the beam current passing through the foil. Since the intensity distribution is expressed on a per incident electron basis, an underestimate in the current will result in an overestimate of the measured intensity.

For electrons to miss the Faraday cup the scattering angle must be larger than 25° . Using the Williams treatment of multiple scattering, Kalil et al.⁴ give the expression for the mean square scattering angle $\bar{\theta}^2$ for a foil thickness t as

$$\bar{\theta}^2 = t \frac{4\pi N Z(Z+1)e^4(1-\beta^2)}{m_o^2 v^4} \ln \left[\frac{Z^{1/3}(Z+1)Nt}{\pi} \left(\frac{h}{m_o v} \right)^2 \right] \quad (30)$$

where N is the atomic density, Z the atomic number, e the electronic charge, m_o the rest mass of the electron, and the other symbols have their usual meaning.

The mean square scattering for 25-kev electrons by a 1270-Å copper foil, according to Equation (30), is 31° . While the Williams treatment probably is not accurate for such large angles, it does indicate that the scattering at 25 kev is significant and probably results in some fraction of the incident electron beam missing the Faraday cup.

⁴The h in the log term of Equation 50 in reference 9 of Chapter IV was incorrectly written as h .

Germanium. The results for a single foil of germanium, 690 Å thick, are shown along with the theoretical values in Figures 26, 27, and 28 and for the same energies as used previously. The theoretical results were calculated using the optical data of Archer and Rustgi, Nodvik, and Weissler.⁵ Again the experimental results for an energy of 25 kev exceed the values predicted by the transition radiation theory. However, at 60 and 100 kev the agreement is seen to be excellent. The same arguments regarding bremsstrahlung and electron scattering apply here, although the scattering angle in the case of germanium foils is less than that for copper because of the smaller thickness and atomic density.

The confidence in the theoretical values for the radiation from germanium is higher than that from copper because of the close agreement in the optical constants measured by Archer and by Rustgi, Nodvik, and Weissler.⁵

Silver. In many aspects, silver was the most interesting metal studied. Its unusual optical properties are responsible for striking features in the emission spectrum. The transparency in the wavelength region near 3200 Å permits observation of the transition radiation produced at both vacuum-foil boundaries. Thus, interference phenomena can be observed in the silver spectrum for particular values of foil thickness. For this reason the spectral distribution for a series of

⁵R. J. Archer, Phys. Rev. 110, 354 (1958); Om. P. Rustgi, J. S. Nodvik, and G. L. Weissler, Phys. Rev. 122, 1131 (1961).

UNCLASSIFIED
ORNL-LR-DWG 79298

Figure 26. Theoretical and experimental photon intensity for 690- $\text{\AA}$ germanium foil at 25 kev.

UNCLASSIFIED
ORNL-LR-DWG 79299

Figure 27. Theoretical and experimental photon intensity for 690- $\text{\AA}$ germanium foil at 60 kev.

UNCLASSIFIED
ORNL-LR-DWG 79300

Figure 28. Theoretical and experimental photon intensity for 690-Å germanium foil at 100 kev.

different foil thicknesses was determined. The data from one of these foils obtained at three different energies are shown in Figures 29, 30, and 31. The optical data used were obtained from the work of Ehrenreich and Philipp.⁶ The sharp peak that characterizes the silver spectrum is apparent in both the experimental and theoretical results at all of the energies for which data were obtained. In these figures the theoretical curves were adjusted for spectrometer resolution as described in Chapter V. As in the case of all of the metals whose emission spectrum was measured, the agreement between theory and experiment is poorest at low energies and improves as the beam energy is increased. At the higher energies the only features of the experimental and theoretical spectra which do not seem to be compatible are the magnitude and width of the characteristic peak at a wavelength slightly in excess of 3300 Å. The theory predicts a peak much narrower than that found experimentally and which has a magnitude about twice that observed. The reason for the discrepancy is unknown.

The emission spectrum of silver is also characterized by a pronounced minimum at a wavelength of about 3200 Å. This minimum is also predicted by theory, although at a wavelength 100 Å higher. The theoretical photon intensity at the minimum is dependent upon the beam energy, the dip becoming more pronounced as the energy is increased. This effect is not obvious in the experimental data, probably because of the larger experimental errors associated with measuring the lower intensities.

⁶H. Ehrenreich and H. R. Philipp, Phys. Rev. 128, 1622 (1962).

UNCLASSIFIED
ORNL-LR-DWG 79301

Figure 29. Theoretical and experimental photon intensity for 710- $\text{\AA}$ silver foil at 25 kev.

UNCLASSIFIED
ORNL-LR-DWG 79302

Figure 30. Theoretical and experimental photon intensity for 710- $\text{\AA}$ silver foil at 60 kev.

Figure 31. Theoretical and experimental photon intensity for 710- $\text{\AA}$ silver foil at 100 kev.

Tin. The spectral distribution of the photon intensity from a 335-Å tin foil is shown in Figures 32, 33, and 34 for the same energies as used previously. The optical properties were obtained from the work of Quincke and Erochin.⁷ These data are interesting because the disparity between theory and experiment at low beam energies almost disappears at the long wavelengths. In addition, at 60 and 100 kev the experimental results are significantly lower than the theoretical values although the general shape of the two spectra are similar. Another series of data was obtained for a 1370-Å tin foil and the same discrepancy was observed. The experimental procedures followed in obtaining these data were no different than those followed in the cases of other metals, and for this reason the discrepancies must be attributed to errors in the optical constants used in evaluating the theory. It would not be surprising if these were in error as the data were obtained over 50 years ago when the techniques of preparing clean metal surfaces were not as advanced as those in contemporary use.

Antimony. Experimental data were obtained for a single 1600-Å thick foil of antimony at the same energies as for the other metals. The antimony foil was prepared inside the target chamber and all of the data were obtained with the foil mounted on a Formvar substrate. A separate investigation of the light emitted by bare Formvar under

⁷G. Quincke, Ann. d. Phys. 23, 142 (1884); P. Erochin, Ann. d. Phys. 39, 213 (1912).

UNCLASSIFIED
ORNL-LR-DWG 79304

Figure 32. Theoretical and experimental photon intensity for 340- $\text{\AA}$ tin foil at 25 kev.

Figure 33. Theoretical and experimental photon intensity for 340- $\text{\AA}$ tin foil at 60 kev.

UNCLASSIFIED
ORNL-LR-DWG 79306

Figure 34. Theoretical and experimental photon intensity for 340- $\text{\AA}$ tin foil at 100 kev.

electron bombardment revealed a faint broad spectrum of light with a maximum intensity of about 0.1 ev/elec-ster-cm at a wavelength of approximately 4200 Å. Since the data are taken with the metal surface between the Formvar and the spectrometer, the light from the Formvar may be neglected in the analysis of the data. The results are shown in Figures 35, 36, and 37 for energies of 25, 60, and 100 kev. The optical constants used were those of Quincke, Hass, and Chatterjee and Prasad.⁸ Comparisons between theory and experiment cannot be made below 4300 Å because of the lack of optical data for antimony in this region. However, in the region for which data are available, the same observations are made as for other metals—namely, a good agreement at the medium and high energies.

Dependence on Electron Energy

The dependence of the photon intensity on the electron energy is quite different for each of the forms of radiation considered, provided the wavelength at which this effect is studied is far from the plasma wavelength, λ_p . If the angle is held fixed, the contribution of Cherenkov radiation may be neglected with the result that all of the radiation may be attributed to transition radiation and the parallel component of bremsstrahlung. Since transition radiation varies roughly linearly with energy and bremsstrahlung varies inversely with energy, an

⁸G. Quincke, Ann. d. Phys. 23, 142 (1884); G. Hass, Ann. d. Phys. 31, 245 (1938); L. M. Chatterjee and K. N. Prasad, Current Sci. 13, 177 (1944).

Figure 35. Theoretical and experimental photon intensity for 1600-Å antimony foil at 25 kev.

UNCLASSIFIED
ORNL-LR-DWG 79314

Figure 36. Theoretical and experimental photon intensity for 1600- $\text{\AA}$ antimony foil at 60 kev.

UNCLASSIFIED
ORNL-LR-DWG 79315

Figure 37. Theoretical and experimental photon intensity for 1600-Å antimony foil at 100 kev.

investigation of the energy dependence of the photon intensity should help in identifying the two sources of light. The experimental data for each of the foils whose emission spectrum was presented in the last section are shown in Figures 38 through 42 along with the corresponding theoretical values. The wavelength at which these data were obtained was chosen within the region of maximum efficiency of the optical system. The optical constants used in the theoretical calculations were selected from those available on the basis of the best fit with the experimental data.

In all cases the intensity is seen to vary linearly with energy in the region between 40 and 100 kev. In addition, the difference in intensities is within the experimental error of the measurements. The disparity between experiment and theory at 25 kev is clearly evident on each of the five curves.

Dependence on Foil Thickness

Transition radiation theory predicts that, for small ϵ_2 and thin foils, the photon intensity exhibits an oscillatory dependence upon foil thickness. This condition is realized in thin silver foils at a wavelength near 3315 Å as ϵ_2 reaches a minimum of 0.2 at that point. To investigate this effect a series of foils was prepared with thicknesses ranging around the predicted peak near 600 Å. The experimental data for energies of 60 and 100 kev for $\lambda = 3315$ Å are shown in Figures 43 and 44 along with the adjusted theoretical values calculated for the same experimental conditions. Poor agreement between the calculated and

Figure 38. Energy dependence of photon intensity for 1270-Å copper foil.

Figure 39. Energy dependence of photon intensity for 690-Å germanium foil.

UNCLASSIFIED
ORNL-DWG 63-43

Figure 40. Energy dependence of photon intensity for 710-Å silver foil.

UNCLASSIFIED
ORNL-DWG 63-44

Figure 41. Energy dependence of photon intensity for 1270-Å tin foil.

UNCLASSIFIED
ORNL-DWG 63-45

Figure 42. Energy dependence of photon intensity for 1600-Å antimony foil.

UNCLASSIFIED
ORNL-DWG 63-46

Figure 43. Thickness dependence of photon intensity for silver at 60 kev.

UNCLASSIFIED
ORNL-DWG 63-47

Figure 44. Thickness dependence of photon intensity for silver at 100 kev.

measured intensities is expected as it was shown earlier that the absolute agreement was found to be poor in the vicinity of the peak. However, the general behavior of the data as the thickness is varied is of interest. To facilitate a comparison with the theoretical curves, the experimental data were adjusted upwards by a factor of 1.75 to bring the data points into closer agreement in magnitude with the theoretical curves. The agreement is not sufficiently good to be of much use in verifying the oscillatory behavior of transition radiation. As seen in the figures the theory predicts a shift in the maximum intensity of more than $100 \text{ \AA}$ when the energy is increased from 60 to 100 kev. The 100-kev data seem to suggest the presence of a maximum but the data points are insufficient in number for this to be considered conclusive. At 60 kev there is one point to the left of the theoretical maximum, but it is not far enough to the left for the theoretical intensity to have fallen much below its maximum value. The other data points definitely indicate a decrease in intensity which is in accord with the theory.

Thus, it may be concluded, on the basis of admittedly meager data, that the general shape of the theoretical curve is in accord with experimental results but that there is an unexplained disagreement between the magnitudes by a factor of almost two.

II. BREMSSTRAHLUNG

The two theories according to which the photon intensity from bremsstrahlung may be estimated are those of Gluckstern, Hull, and

Breit,⁹ which accounts only for the production of the radiation, and that of Ritchie¹⁰ which takes into account the production as well as the modifying effects of the medium. While bremsstrahlung has both a parallel and a perpendicular component of polarization, the presence of transition radiation in any experimental measurement makes identification of the parallel component virtually impossible except for small observation angles. As the experimental equipment used in the course of this investigation was fixed at an angle of 30°, the study was confined only to the perpendicular component.

The photon intensity according to the Gluckstern-Hull theory was obtained by the expression

$$\frac{d^2 E}{d\Omega d\lambda} = \frac{hc}{\lambda} Nt d\sigma \quad (31)$$

where N is the atomic density, t is the foil thickness, and $d\sigma$ is the differential cross section. The differential cross sections for the parallel and perpendicular components are obtained from Equations (14) and (15), respectively. The intensity according to Ritchie's theory was obtained from Equations (17), (18), and (19) by integration Equations (17) and (18) over the foil thickness. The number distributions per unit frequency were converted to intensity distributions per unit wavelength and then reduced to the following for the per-

⁹R. L. Gluckstern, M. H. Hull, and G. Breit, Phys. Rev. 90, 1026 (1953); R. L. Gluckstern and M. H. Hull, Phys. Rev. 90, 1030 (1953).

¹⁰R. H. Ritchie, To be published in J. Math. Phys.

pendicular component:

$$\begin{aligned} \frac{d^2 E_{\perp}}{d\Omega d\lambda} = & \frac{e^2 \beta^2 \langle \Theta^2 \rangle \cos^2 \theta}{2\pi^2 \lambda} \cdot \frac{1}{|D|^2} \left[-\frac{|\mu + \sigma|^2}{2\sigma_1} \left(1 - e^{2\sigma_1 t}\right) \right. \\ & + \frac{|\mu - \sigma|^2}{2\sigma_1} \left(1 - e^{-2\sigma_1 t}\right) + \frac{(\mu - \sigma)(\mu + \sigma^*)}{i2\sigma_R} \left(1 - e^{i2\sigma_R t}\right) \\ & \left. - \frac{(\mu + \sigma)(\mu - \sigma^*)}{i2\sigma_R} \left(1 - e^{-i2\sigma_R t}\right) \right] \end{aligned} \quad (32)$$

where $D = (\mu + \sigma)^2 e^{-i\sigma t} - (\mu - \sigma)^2 e^{i\sigma t}$, and the other quantities are defined in Equation (8). The parallel component was reduced to

$$\frac{d^2 E_{\parallel}}{d\Omega d\lambda} = \frac{e^2 \beta^2 \langle \Theta^2 \rangle \cos^2 \theta}{2\pi^2 \lambda} \cdot \frac{1}{|\xi|^2} \cdot I$$

where

$$\xi = [(\mu - \sigma)^2 e^{i\sigma t} - (\mu + \sigma)^2 e^{-i\sigma t}] \cdot [(\epsilon\mu - \sigma)^2 e^{i\sigma t} - (\epsilon\mu + \sigma)^2 e^{-i\sigma t}],$$

$$\begin{aligned} I = & -\frac{|\eta_1|^2}{2\sigma_1} \left(1 - e^{2\sigma_1 t}\right) + \frac{|\eta_2|^2}{2\sigma_1} \left(1 - e^{-2\sigma_1 t}\right) \\ & + \frac{\eta_1 \eta_2^*}{2i\sigma_R} \left(1 - e^{-2i\sigma_R t}\right) - \frac{\eta_1^* \eta_2}{2i\sigma_R} \left(1 - e^{2i\sigma_R t}\right), \end{aligned}$$

$$\eta_1 = \left[\mu(\mu + \sigma)(\epsilon\mu - \sigma)^2 + (\epsilon - 1)(1 - \mu^2)(\epsilon\mu + \sigma)(\mu + \sigma) - 4\mu\sigma(\epsilon - 1)(1 - \mu^2) \right] e^{i\sigma t} - \left[\mu(\mu + \sigma)(\epsilon\mu + \sigma)^2 + (\epsilon - 1)(1 - \mu^2)(\epsilon\mu + \sigma)(\mu + \sigma) \right] e^{-i\sigma t},$$

and

$$\eta_2 = \left[\mu(\mu - \sigma)(\epsilon\mu + \sigma)^2 + (\epsilon - 1)(1 - \mu^2)(\epsilon\mu - \sigma)(\mu - \sigma) + 4\mu\sigma(\epsilon - 1)(1 - \mu^2) \right] e^{-i\sigma t} - \left[\mu(\mu - \sigma)(\epsilon\mu - \sigma)^2 + (\epsilon - 1)(1 - \mu^2)(\epsilon\mu - \sigma)(\mu - \sigma) \right] e^{i\sigma t}.$$

In these expressions σ_R and σ_I denote the real and imaginary parts of σ , respectively, and the * signifies the complex conjugate.

Equations (31), (32), and (33) were programmed for solution by digital computers. The wavelength, with corresponding values for the optical constants n and k , foil thickness, energy, and angle were left as input parameters so that the theoretical results could be obtained for a variety of possible experimental arrangements.

The mean square scattering angle per unit thickness was computed from the simplified expression given by Fermi,¹¹

$$\langle \Theta^2 \rangle = \frac{8\pi N Z^2 e^4}{v_p^2} \ln \frac{b_{\max}}{b_{\min}} \quad (34)$$

where N is the atomic density, Z is the atomic number of the foil

¹¹E. Fermi, Nuclear Physics (Chicago: University of Chicago Press, 1950) Revised Edition.

material, e is the electronic charge, v is the velocity of the incident charge, and p is its momentum. The log term containing the ratio of the impact parameters was calculated from the recent work of Lewis,¹²

$$\ln \frac{b_{\max}}{b_{\min}} = (1 + \Gamma) \ln \left(\frac{2}{\Gamma} + 1 \right) \quad (35)$$

where

$$\Gamma = \frac{Z^{2/3}}{2\beta^2} \left(\frac{e^2}{\hbar c} \right).$$

An attempt was made to compare the intensity predicted by the two theories in a situation where the dielectric properties of the medium would have no effect on the intensity outside the material. For this case n was taken to be 1.0 so that refraction and internal reflection would not occur and k was taken $\ll 1$ so as to minimize absorption within the medium. The agreement was excellent at the low energies but the Gluckstern-Hull theory predicted appreciably higher intensities than Ritchie's theory at energies above 25 kev. The difference was attributed to the relativistic effects which are not included in the Ritchie theory. This was more clearly demonstrated by considering Equation (31) in the limiting case $\beta \ll 1$. Each component of polarization was found to agree within several per cent with its counterpart in the Ritchie theory at all energies up to 100 kev.

Since the Ritchie theory takes into account the optical properties

¹²H. Lewis, Phys. Rev. 78, 526 (1950).

of the medium, it should be more accurate than the Gluckstern-Hull theory. Consequently, an attempt was made to modify Ritchie's theory by the inclusion of the relativistic terms appearing in the Gluckstern-Hull equations. This amounted to the multiplication of Equation (32) by the expression $(1 - \beta^2) \cdot |1 - \beta\sigma|^{-2}$, and Equation (33) by the expression $(1 - \beta^2) \cdot |\sigma - \beta|^2 \cdot |1 - \beta\sigma|^{-4}$. In addition, a factor of $1 - \beta^2$ was used in computing Γ in Equation (35). The complex angle σ replaces the $\cos \theta$ of the Gluckstern-Hull theory in these correction factors.

A striking example of the effects which the optical properties of the medium have upon the photon intensity is shown in Figure 45 for a 710-Å silver foil at a beam energy of 40 kev. Here the intensities for both components of polarization are shown for the two bremsstrahlung theories. With Ritchie's treatment both components are modified with the parallel component being affected the more strongly. It is interesting that the bremsstrahlung spectrum for silver also exhibits a relatively intense peak but at a wavelength 200 Å below the transition radiation peak. Except for this peak the general shapes of the spectra calculated by the two bremsstrahlung theories are seen to be similar. The $1/\lambda$ dependence is clearly exhibited and the strong effect of absorption by the material is reflected by the general lower intensity level predicted by the Ritchie theory.

Spectral Distribution

Experimental verification of the bremsstrahlung theories in the optical region is a difficult task. The lack of intensity results in

UNCLASSIFIED
ORNL-DWG 63-48

Figure 45. Perpendicular component of bremsstrahlung calculated for a 710- $\text{\AA}$ silver foil at 25 kev.

signals which are almost at the noise level where precise measurements are virtually impossible to make. Because of this low intensity it is necessary to do everything possible to enhance the production of the radiation. This would suggest the use of a thick foil of a high Z material, low beam energy, and observation of the short wavelength light coming off in the forward direction. However, high Z foils and low beam energies are exactly the conditions conducive to the electron scattering which distorts the measurements necessary for a valid comparison with theory.

The effects of scattering are evident in Figures 46 and 47 which show the perpendicular component of the light emitted from a 1370-Å tin foil at beam energies of 25 and 80 kev, respectively. The solid curve in these figures is the perpendicular component of the Gluckstern-Hull theory plotted on the same scale. Even at 80 kev the experimental points, while lower in intensity, are still higher than the Gluckstern-Hull theory which, itself, is higher than would be expected in the case of a real absorbing medium. It is not clear why scattering tends to increase the apparent photon intensity more at the short wavelength end of the spectrum. The spectrum shows the general $1/\lambda$ dependence predicted by theory.

Dependence on Electron Energy

An attempt to eliminate some of the effects of scattering was made by using somewhat thinner foils of a metal with a lower absorption coefficient. The data were taken with an 850-Å silver foil at a wave-

UNCLASSIFIED
ORNL-DWG 63-49

Figure 46. Bremsstrahlung intensity for a 1370-Å tin foil with electron energy of 25 kev.

Figure 47. Bremsstrahlung intensity for a 1370-Å tin foil with electron energy of 80 kev.

length of $4300 \text{ \AA}$. The sensitivity of the optical equipment was a maximum in this region, and this wavelength is rather far removed from the region in which scattering seems to contribute its greatest effect. It should be pointed out that the net photomultiplier currents in this case were only about 25 per cent of the background dark current and not more than a factor of 2 above the random fluctuations in the recorded current. Therefore, the errors associated with these measurements are large. The data are shown in Figure 48 along with the curves calculated from the two theories. The experimental points are about one order of magnitude greater than the Ritchie theory and about one order of magnitude below the Gluckstern-Hull theory. The $1/E$ falloff in intensity is observed in contrast to the linear dependence on energy for transition radiation, as was shown in Figures 39 through 43.

Dependence on Foil Thickness

Since the production of bremsstrahlung is a volume effect, it varies linearly with the foil thickness. However, the radiation which is observed, i.e., that which escapes from the foil, is linear with thickness only in the limit of small thickness. Of course, the Gluckstern-Hull treatment predicts a linear dependence for all thicknesses as the absorptive properties of the medium are not taken into account. The theoretical and experimental results for silver foils at a beam energy of 40 kev and a wavelength of $4300 \text{ \AA}$ are shown in Figure 49. Clearly evident is the linear increase in intensity exhibited by the Gluckstern-Hull treatment and the relative independence of thickness

UNCLASSIFIED
ORNL-DWG 63-51

Figure 48. Energy dependence of bremsstrahlung intensity with an 850-Å silver foil at wavelength of 4300 Å.

Figure 49. Thickness dependence of bremsstrahlung intensity from silver at energy of 40 kev and wavelength of 4300 Å.

by the Ritchie theory. Again, the experimental data fall between the two theoretical curves but the constant photon intensity is in agreement with Ritchie's result.

III. PLASMA RADIATION

Of the five metals whose emission spectra were studied, only silver exhibited a characteristic which could be suggestive of a resonance process. This characteristic takes the form of a relatively sharp and intense emission peak near $3300 \text{ \AA}$ and is clearly shown in the wavelength distributions of the photon intensity exhibited earlier in Figures 29, 30, and 31. As was mentioned in Chapter II, this peak has also been observed by other experimenters, several of whom have attributed it to decay of the oscillations of the free electron gas at the characteristic plasma frequency. Support for this conclusion was achieved through the apparent agreement between plasma radiation theory and these experiments, particularly with regard to the angular distribution of the light as well as its polarization and dependence upon the foil thickness. In addition, a characteristic energy loss, in silver, of 3.5 to 3.6 eV had been observed by several experimenters and, since this corresponds reasonably well to the photon energy of 3.75 eV, this agreement was taken to be convincing evidence of the plasma radiation explanation of the observed emission peak.

Earlier, it was shown that the peak also was predicted by the generalized transition radiation theory and that, with the single exception of the photon intensity, all characteristics observed

experimentally were reasonably well predicted by the theory. This does not negate the possibility that the emission peak is due to plasma effects as transition radiation theory does not provide a clear picture of the physical processes involved in the emission of the radiation. For this it is necessary to consider the optical characteristics of the metal and the processes upon which they depend.

Fröhlich and Pelzer¹³ showed that, for a metal whose optical properties near the plasma frequency are determined essentially by free electron contributions, one should expect an energy loss in steps of $\hbar\omega_p$. They further showed that the quantity $nk/(n^2 + k^2)^2$ has a sharp maximum in such a case. The fact that this quantity does peak near 3300 Å when the optical constants of silver are used tends to indicate that the discrete loss is associated with plasma effects. Later, Kanazawa¹⁴ considered this problem quantum mechanically and reported that, in addition to this peak associated with the normal or bulk loss, the quantity $nk(4 + n^2k^2)/(n^2 - k^2 + 1)^2$ should peak at the so-called reduced or surface loss.¹⁵ With the appropriate values for n and k , this occurs at 3.4 eV in the case of silver. Kanazawa also indicated that, since the width of the normal loss is about 0.8 eV for silver, the two losses would not be resolved by experimental studies. Later

¹³H. Fröhlich and H. Pelzer, Proc. Phys. Soc. (London) A68, 525 (1955).

¹⁴H. Kanazawa, Prog. Theor. Phys. 26, 851 (1961).

¹⁵R. H. Ritchie, Phys. Rev. 106, 874 (1957).

work by Hattori and Yamada¹⁶ indicated that the intensity of the reduced loss was much greater than the bulk loss in the range of foil thicknesses used in the experimental studies. On the basis of experimental studies of the dependence of the loss intensity on the scattering angle and thickness, Kunz¹⁷ concluded that the observed loss at 3.6 ev was due to excitation of the surface plasmon.

The fact that the two losses occur close together argues against the explanation that plasma oscillations are primarily responsible for the effects observed, for if this were the case then theory predicts the lowered loss to be $1/\sqrt{2}$ times the normal loss. This argument is strengthened by the significant dissimilarity between the optical properties of silver and those of a free electron gas.

Ehrenreich and Philipp,¹⁸ in their detailed study of the optical properties of silver, have discussed the contribution of both the free and bound electrons to the real part of the dielectric constant. They concluded that the optical properties in the region between 3.5 and 4.0 ev are determined by the cooperative behavior of the d band electrons as well as the conduction electrons. The fact that ϵ_1 vanishes in this region is not evidence of the free electron resonance, i.e., the mechanism responsible for plasma radiation. This resonance occurs at 9.2 ev ($\sim 1350 \text{ \AA}$) and is far removed from the region in which detailed

¹⁶M. Hattori and K. Yamada, J. Phys. Soc. Japan 18, 200 (1963).

¹⁷C. Kunz, Z. Phys. 167, 53 (1962).

¹⁸H. Ehrenreich and H. R. Philipp, Phys. Rev. 128, 1622 (1962).

studies of the emission spectra have been carried out.

These considerations cast doubt on the plasma radiation explanation of the peak in the emission spectra of silver. The peak seems more likely to be due to an interband transition which results in the vanishing of ϵ_1 in the vicinity of 3300 Å.

There is additional evidence against the plasma oscillation explanation. Recent experimental studies of the characteristic energy losses in silver have shown that a characteristic loss line at 3.7 ev occurs in silver vapor as well as in the bulk metal.¹⁹ It would be difficult to account for this on the basis of oscillations within the free electron gas of the metal. On the basis of these data the 3.7-ev loss was ascribed to the excitation of a 5s-5p transition.

IV. CHERENKOV RADIATION

As mentioned earlier, it would be a difficult task to identify the Cherenkov radiation because of the strong background of transition radiation. In addition, this radiation is produced only for particular combinations of n and k , and even with such a combination the emission occurs at only a single angle. Consequently, because of the fixed angle nature of the experiment, a deliberate attempt to identify Cherenkov radiation was not carried out. However, it should be emphasized that the generalized transition radiation theory used in the comparisons carried out earlier includes Cherenkov effects. Thus, both

¹⁹H. Boersch, J. Geiger, H. Hellwig, and H. Michel, Z. Phys. 169, 252 (1962).

theory and experiment accounted for the effect if it occurred although neither could identify it uniquely.

CHAPTER VIII

SUMMARY

The visible and ultraviolet light emitted by thin metallic films while undergoing bombardment by high energy electrons has been investigated experimentally. The metals studied were copper, germanium, silver, tin, and antimony. The absolute photon intensity was measured and its dependence upon the four parameters of polarization, wavelength, electron energy, and foil thickness was determined. These results were compared with the theoretical intensities of transition radiation and the optical portion of the bremsstrahlung spectrum.

The spectral distribution of the photon intensity polarized parallel to the plane of incidence agrees well with the theoretical transition radiation intensity at energies between 40 and 100 kev. Below 40 kev the experimentally measured intensities exceed theoretical values by about a factor of 2. This discrepancy is attributed to electron scattering within the metal foil. Even at low energies, however, the shape of the spectral distribution of the intensity exhibits the predicted decrease with increasing wavelength. In the case of silver the spectrum is characterized by a relatively intense peak near 3300 Å. This peak in the emission spectrum is predicted by transition radiation theory when the appropriate optical constants are supplied, although the theoretical intensity is about 75 per cent greater than that found experimentally. This deviation is shown to be larger than the probable error of the measurement and, for this reason, it is

attributed to some unknown damping process.

For all of the metals studied, the dependence of the photon intensity upon energy was found to be linear and, except for the measurements at 25 kev, the slope of the curve of intensity vs energy agreed with that calculated from the theory.

The thickness dependence of the photon intensity was investigated using silver foils with thicknesses varying around the peak near 600 Å. The study was carried out at the wavelength of the maximum of the characteristic peak as theory predicted an oscillatory behavior of the photon intensity at this wavelength. The experimental data were only suggestive of the predicted oscillatory behavior. The lack of confirmation can probably be accounted for by the sparsity of experimental data. Measurements in this region were more difficult to carry out because of the more critical effect of foil thickness and the narrowness of the characteristic silver peak.

Although the optical portion of the bremsstrahlung spectrum is composed of radiation with both a parallel and a perpendicular component, the intensities are much less than the transition radiation intensity. In a typical case the transition radiation intensity is of the order of 10 ev/elec-steradian-cm, whereas the corresponding parallel bremsstrahlung component is calculated to be only 0.1 to 1 per cent as large. It is for this reason that bremsstrahlung may be neglected in comparison with transition radiation when the measurements are confined to the parallel polarized components from elements of low and medium atomic number.

As transition radiation is predicted to be completely polarized

in the plane of incidence, the experimental investigation of bremsstrahlung is carried out best using the perpendicular component. The experimental results were compared both with the Gluckstern-Hull relativistic theory and with the Ritchie theory of bremsstrahlung from a dielectric medium. In general, it was found that in the case of thin films, the intensities determined experimentally were less than those predicted by the Gluckstern-Hull theory and greater than those calculated from Ritchie's theory. Here, electron scattering effects were even more important as the intensities of the perpendicular components were less than the transition radiation intensities by more than an order of magnitude. The effect of scattering was found to increase the apparent photon intensity. While the agreement between the Ritchie theory and experiment was found to be poor in terms of absolute magnitude, the general features of the theory were confirmed. This included an inverse dependence on the beam energy, constant intensity for various foil thicknesses, and the spectral distribution predicted by the theory for a dispersive medium.

The characteristic peak in the emission spectrum of silver was considered from the standpoint of Ferrell's theory of plasma radiation. Arguments against this popular explanation were supported by a consideration of the contribution of interband transitions to the optical constants. Recent optical data on silver were cited to show that the free electron plasma frequency (the basis of Ferrell's theory) was much higher than the range of frequencies considered in this study.

Finally, the possibility of observing Cherenkov radiation was

considered. Inasmuch as all of the experimental data were obtained at a fixed angle of 30° , it would be unlikely for this radiation to have been observed. The possibility of the light having been produced was not discounted, and it was pointed out that its contribution to the parallel component of the photon intensity was properly accounted for by the generalized theory of transition radiation.

This investigation has demonstrated the validity of the generalized transition radiation theory. It has also suggested that the Ritchie theory of bremsstrahlung from dielectric media correctly accounts for the general features of the experimental observations, although there is an unexplained discrepancy between the observed and the calculated yields. While this study has not confirmed the existence of the predicted plasma radiation, it has done nothing to dispel the idea that such radiation exists.

Although transition radiation theory has been shown to be well founded, it would be of considerable interest to obtain angular distribution measurements. This is an obvious next step. Also, additional data on silver foils in the vicinity of the characteristic peak would be of benefit.

In connection with angular distribution measurements the ratio of bremsstrahlung intensity to transition radiation intensity can be greatly increased by making the measurements at small angles. Since the transition radiation intensity goes to zero as the observation angle goes to zero, the advantage of using the greater intensity of the parallel component of bremsstrahlung can be realized. In addition, it

may be possible to reduce the photomultiplier dark current to permit more accurate measurements to be made of the bremsstrahlung intensity.

With the availability of angular distribution equipment, the possibility of observing Cherenkov radiation from metals would become of some interest. If this does prove to be feasible then a number of interesting effects could be investigated which heretofore have been studied only in theory.

Finally, the question of plasma radiation needs to be answered. A study of the emission spectra of the alkali metals would seem to afford the best opportunity of observing this radiation, as here the free electron theory of metals holds particularly well. The attendant experimental problems of carrying out the measurements in the ultra high vacuum region are obvious.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

BIBLIOGRAPHY

- Amatuni, A. Ts., and N. A. Korkhmazyan, JETP 12, 703 (1961).
- Arakawa, E. T., et al. "Optical Emission from Metal Foils Irradiated by High Energy Electrons." Paper presented at the 2nd International Congress of Radiation Research, Harrogate, England, August 5-11, 1962.
- Archer, R. J., Phys. Rev. 110, 354 (1958).
- Askar'ian, G. A., JETP 2, 334 (1955).
- Askar'ian, G. A., JETP 3, 613 (1956).
- Askar'yan, G. A., JETP 15, 943 (1962).
- Avery, D. G., Nature 163, 916 (1949).
- Barsukov, K. A., JETP 10, 787 (1960).
- Beck, G., Phys. Rev. 74, 795 (1948).
- Blackstock, A. W., "Discrete Electron Energy Losses in Thin Metallic Foils," ORNL-1910 (June 16, 1955).
- Blackstock, A. W., R. D. Birkhoff, and M. Slater, Rev. Sci. Instr. 26, 274 (1955).
- Blois, M. S., Jr., and L. M. Rieser, Jr., J. Appl. Phys. 25, 338 (1954).
- Bobrinev, V., and V. Braginskii, Acad. Sci. USSR (Proc.) 3, 1179 (1958).
- Boeckner, C., J. Res. NBS 9, 413 (1932).
- Boersch, H., C. Radloff, and G. Sauerbrey, Phys. Rev. Letters 7, 52 (1962).
- Boersch, H., C. Radloff, and G. Sauerbrey, Z. Phys. 165, 464 (1961).
- Boersch, H., J. Geiger, H. Hellwig, and H. Michel, Z. Phys. 169, 252 (1962).
- Bohm, D., and D. Pines, Phys. Rev. 82, 625 (1951).
- Brown, R. W., P. Wessel, and E. P. Trownson, Phys. Rev. Letters 5, 472 (1961).

- Chatterjee, L. M., and K. N. Prasad, *Current Sci.* 13, 177 (1944).
- Chaudhri, R. M., and M. Y. Khan, *Nature* 192, 647 (1961).
- Cherenkov, P. A., *C. R. Acad. Sci., USSR* 2, 451 (1934).
- Cohn, W. M., *Z. Phys.* 70, 662 (1931).
- Cohn, W. M., *Z. Phys.* 72, 392 (1931).
- Cohn, W. M., *Z. Phys.* 73, 662 (1931).
- Cohn, W. M., *Z. Phys.* 75, 544 (1932).
- Dake, H. C., and J. DeMent. Fluorescent Light and Its Applications.
New York: Chemical Publishing Co., 1941.
- Dnestrovskii, Iu. N., and D. P. Kostomarov, *Acad. Sci. USSR (Proc.)* 2,
442 (1957).
- Dnestrovskii, Iu. N., and D. P. Kostomarov, *Acad. Sci. USSR (Proc.)* 4,
132 (1959).
- Dnestrovskii, Iu. N., and D. P. Kostomarov, *Acad. Sci. USSR (Proc.)* 4,
158 (1959).
- Donaldson, W. K., and A. Khamsavi, *Nature* 159, 228 (1947).
- Ehrenreich, H., and H. R. Philipp, *Phys. Rev.* 128, 1622 (1962).
- Erochin, P., *Ann. d. Phys.* 39, 213 (1912).
- Fainberg, Ia. B., and N. A. Khizhniak, *JETP* 5, 720 (1957).
- Fermi, E. Nuclear Physics. Chicago: University of Chicago Press,
1950. Revised Edition.
- Ferrell, R. A., *Phys. Rev.* 111, 1214 (1958).
- Ferrell, R. A., and E. A. Stern, *Am. J. Phys.* 30, 810 (1962).
- Footé, P. D., W. F. Meggers, and R. L. Chenault, *J. Opt. Soc. Am.* 9,
541 (1924).
- Frank, A. L., E. T. Arakawa, and R. D. Birkhoff, *Phys. Rev.* 126, 1947
(1962).
- Frank, A. L., et al., "Optical Emission from Irradiated Thin Metallic
Foil," ORNL-3114 (July 2, 1962).

- Frank, I., and I. G. Tamm, C. R. Acad. Sci., USSR 14, 109 (1937).
- Frank, I., and V. Ginzburg, J. Phys. USSR 9, 353 (1945).
- Frank, I. M., Sov. Phys. Uspekhi 14, 740 (1962).
- Fröhlich, H., and H. Pelzer, Proc. Phys. Soc. (London) A68, 525 (1955).
- Garibian, G. M., JETP 6, 1079 (1958).
- Garibian, G. M., and G. A. Chalikian, JETP 8, 894 (1959).
- Garibian, G. M., JETP 8, 1003 (1959).
- Garibyan, G. M., JETP 10, 372 (1960).
- Garibyan, G. M., and I. Ya. Pomeranchuk, JETP 10, 1290 (1960).
- Garibyan, G. M., JETP 12, 237 (1961).
- Ginzburg, V. L., and I. Frank, J. Exp. Th. Phys. USSR 16, 15 (1946).
- Ginzburg, V. L., JETP 6, 1096 (1958).
- Glasser, O. Dr. W. C. Röntgen. Springfield: C. C. Thomas, 1958.
2nd Edition.
- Gluckstern, R. L., and M. H. Hull, Phys. Rev. 90, 1030 (1953).
- Gluckstern, R. L., M. H. Hull, and G. Breit, Phys. Rev. 90, 1026 (1953).
- Goldsmith, P., and J. V. Jelley, Phil. Mag. 4, 836 (1959).
- Hakki, B. W., and H. J. Krumme, IRE Proc. 49, 1334 (1961).
- Hammer, D. C., E. T. Arakawa, and R. D. Birkhoff, To be published in
Appl. Optics.
- Hass, G., Ann. d. Phys. 31, 245 (1938).
- Hattori, M., and K. Yamada, J. Phys. Soc. Japan 18, 200 (1963).
- Heitler, W. Quantum Theory of Radiation. London: Oxford University
Press, 1949. 2nd Edition.
- Holland, L. Vacuum Deposition of Thin Films. New York: John Wiley and
Sons, 1960.
- Ishiguro, K., J. Phys. Soc. Japan 6, 71 (1951).

- Jelley, J. V. Cherenkov Radiation and Its Applications. London: Pergamon Press, 1958.
- Kalil, F., et al., "Stopping Power of Thin Aluminum Foils for 12 to 127 kev Electrons," ORNL-2731 (September 3, 1959).
- Kanazawa, H., Prog. Theor. Phys. 26, 851 (1961).
- Kaner, E. A., and V. M. Yakovlev, JETP 15, 330 (1962).
- Kapitza, S. P., JETP 12, 954 (1961).
- Klepikov, N. P., Moscow Univ. Vestnik 8, 61 (1951).
- Kramers, A., Phil. Mag. 46, 836 (1923).
- Kunz, C., Z. Phys. 167, 53 (1962).
- Lewis, H., Phys. Rev. 78, 526 (1950).
- Lilienfeld, J. E., Phys. Z. 20, 280 (1919).
- Lilienfeld, J. E., and F. Rother, Phys. Z. 21, 249 (1920).
- Malsch, J., Ann. d. Phys. 7, 360 (1930).
- Mikhalyak, S. "Investigation of Transition Radiation." Unpublished Physical-Mathematical Sciences thesis, M. V. Lomonosov State University, Moscow, USSR, 1961.
- Minor, R. S., Ann. d. Phys. 10, 581 (1903).
- Mohler, F. L., and C. Boeckner, J. Res. NBS 6, 673 (1931).
- Mohler, F. L., and C. Boeckner, J. Res. NBS 7, 751 (1931).
- Mohler, F. L., J. Res. NBS 8, 357 (1932).
- National Bureau of Standards. Precision Measurement and Calibration. United States Department of Commerce, Handbook 77, Vol. III. Washington: Government Printing Office, 1961.
- Pafomov, V. E., JETP 6, 829 (1958).
- Pafomov, V. E., JETP 9, 1321 (1959).
- Pafomov, V. E., Acad. Sci. USSR (Proc.) 5, 850 (1960).
- Pafomov, V. E., JETP 12, 97 (1961).

- Pfestorf, G., Ann. d. Phys. 81, 906 (1926).
- Pratesi, R., et al., Nuovo Cimento 25, 756 (1962).
- Quincke, G., Ann. d. Phys. 23, 142 (1884).
- Ritchie, R. H., Phys. Rev. 106, 874 (1957).
- Ritchie, R. H., Am. Phys. Soc. (Bull.) 4, 381 (1959).
- Ritchie, R. H., and H. B. Eldridge, Phys. Rev. 126, 1935 (1962).
- Ritchie, R. H., To be published in J. Math. Phys.
- Rother, F., and W. M. Cohn, Phys. Z. 31, 687 (1930).
- Rudberg, E., Proc. Roy. Soc. (London) A127, 111 (1930).
- Rudberg, E., Proc. Roy. Soc. (London) A129, 652 (1930).
- Rudberg, E., and J. C. Slater, Phys. Rev. 50, 150 (1936).
- Rustgi, Om. P., J. S. Nodvik, and G. L. Weissler, Phys. Rev. 122, 1131 (1961).
- Schulz, L. G., J. Opt. Soc. Am. 44, 357 (1954).
- Schulz, L. G., and F. R. Tangerlini, J. Opt. Soc. Am. 44, 362 (1954).
- Seemann, H., Phys. Z. 22, 581 (1921).
- Silin, V. P., and E. P. Fetisov, Phys. Rev. Letters 7, 374 (1961).
- Smith, S. J., and E. M. Purcell, Phys. Rev. 92, 1069 (1953).
- Sommerfeld, A., Ann. d. Phys. 11, 257 (1931).
- Sommermeyer, K., Z. Naturforsch 4a, 440 (1949).
- Steinmann, W., Phys. Rev. Letters 5, 470 (1960).
- Steinmann, W., Z. Phys. 163, 92 (1961).
- Stern, E. A., Phys. Rev. Letters 8, 7 (1962).
- Tamm, Ig., J. Phys. USSR 1, 439 (1939).
- Tate, J. T., Phys. Rev. 34, 321 (1912).

- Ter-Mikaelyan, M. L., and A. D. Gazazyan, JETP 12, 1183 (1961).
- Tolansky, S. Multiple-Beam Interferometry of Surfaces and Films.
London: University of Oxford Press, 1948.
- Tolansky, S. Les Proprieties Optiques des Lames Minces Solids.
Paris: Centre Nationale de la Recherche Scientific, 1950.
- Tolansky, S., Vacuum 2, 231 (1952).
- von Baeyer, O., Phys. Z. 10, 168 (1908).
- von Baeyer, O., Phys. Z. 10, 176 (1908).
- Wainfan, N., N. J. Scott, and L. G. Parrott, J. Appl. Phys. 30, 1604
(1959).
- Wessel, P., Am. Phys. Soc. (Bull.) 6, 310 (1961).
- Williams, E. J., Proc. Roy. Soc. (London) A169, 531 (1939).
- Williams, E. J., Phys. Rev. 58, 292 (1940).
- Worthing, A. G., J. Opt. Soc. Am. 13, 635 (1936).
- Ziemer, P. L., R. M. Johnson, and R. D. Birkhoff, "Measurement of
Stopping Power of Copper by Calorimetric Methods," ORNL-2775
(December 17, 1959).
- Zhelnov, B. L., JETP 13, 117 (1961).

RADIATION EMITTED BY THE SUDDEN COLLAPSE OF THE FIELD OF AN ELECTRIC DIPOLE

The Poynting vector, $\vec{S}$, for an electric dipole may be written in terms of the electric and magnetic field intensities, $\vec{E}$ and $\vec{H}$, respectively, as

$$\vec{S} = \frac{c}{4\pi} \vec{E} \times \vec{H}. \quad (1)$$

Since $|\vec{E}| = |\vec{H}|$ for plane waves, this may be expressed as

$$\vec{S} = \frac{c}{4\pi} H^2 \hat{n} \quad (2)$$

where $\hat{n}$ is the unit vector in the direction of $\vec{S}$. Dropping the vector notation, the total radiation intensity crossing area dA at distance R is given by

$$\begin{aligned} dI &= SR^2 d\Omega \\ &= \frac{c}{4\pi} H^2 R^2 d\Omega \end{aligned} \quad (3)$$

where $d\Omega$ is the solid angle subtended by dA at the source.

To obtain the intensity radiated into $d\Omega$ by waves in the frequency range $d\omega$ about ω , H^2 is replaced by its equivalent in Fourier integral theory, $4\pi|H_\omega|^2$, to obtain

$$\frac{dE}{d\omega} = c|H_\omega|^2 R^2 d\Omega \quad (4)$$

where

$$\vec{H}_\omega = \frac{1}{2\pi} \int_{-\infty}^{\infty} \vec{H} e^{i\omega t} dt.$$

Since the time over which the collision occurs is short, $\omega t \ll 1$ and

$\vec{H}_\omega$ is given approximately by $\frac{1}{2\pi} \int_{-\infty}^{\infty} \vec{H} dt$. $\vec{H}$ may be expressed in terms of

the magnetic vector potential $\vec{A}$ by

$$\vec{H} = \frac{1}{c} \frac{d\vec{A}}{dt} \times \hat{n}, \quad (5)$$

so that $\vec{H}_\omega$ is given by

$$\begin{aligned} \vec{H}_\omega &= \frac{1}{2\pi c} \int_{-\infty}^{\infty} \frac{d\vec{A}}{dt} \times \hat{n} dt \\ &= \frac{1}{2\pi c} \vec{A} \times \hat{n}. \end{aligned} \quad (6)$$

Using this result in the expression for the radiation intensity,

Equation (4) becomes

$$\frac{dE}{d\omega} = c \left[\frac{1}{2\pi c} \vec{A} \times \hat{n} \right]^2 R^2 d\Omega. \quad (7)$$

Using the retarded potential expression for $\vec{A}$,

$$\vec{A} = \frac{1}{cR} \int \vec{j} \left(t - \frac{R}{c} \right) d\tau \quad (8)$$

where $\vec{j}$ is the current. Equation (7) may now be written on a per

wavelength basis as

$$\begin{aligned}\frac{dE}{d\lambda} &= \frac{1}{2\pi\lambda^2} \left[\frac{1}{cR} \int \vec{j} \left(t - \frac{R}{c} \right) \times \hat{n} d\tau \right]^2 R^2 d\Omega \\ &= \frac{1}{2\pi c^2 \lambda^2} \left[\int \dot{q} \vec{v} \times \hat{n} d\tau \right]^2 d\Omega,\end{aligned}$$

which, for velocities lying along the z axis, becomes

$$\frac{dE}{d\lambda} = \frac{1}{2\pi c^2 \lambda^2} \left[\sum qv \right]^2 \sin^2 \theta d\Omega \quad (9)$$

where θ is the polar angle. The total energy radiated per unit wavelength is obtained by integrating over the half space above the boundary,

$$\begin{aligned}\frac{dE}{d\lambda} &= \frac{1}{2\pi c^2 \lambda^2} \int_0^{2\pi} \int_0^{\pi/2} \left[\sum qv \right]^2 \sin^2 \theta \sin \theta d\theta d\phi \\ &= \frac{2}{3c^2 \lambda^2} \left[\sum qv \right]^2\end{aligned} \quad (10)$$

For the annihilation of the dipole, this becomes

$$\frac{dE}{d\lambda} = \frac{2}{3c^2 \lambda^2} \left[ev + (-e)(-v) \right]^2 = \frac{8e^2 v^2}{3c^2 \lambda^2}.$$

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ORNL-3450
UC-34 — Physics
TID-4500 (20th ed.)

INTERNAL DISTRIBUTION

1. Biology Library	146. R. H. Lafferty, Jr.
2-3. Central Research Library	147. C. E. Larson
4. Reactor Division Library	148. A. Meyer
5-6. ORNL - Y-12 Technical Library	149. K. Z. Morgan
Document Reference Section	150. D. R. Nelson
7-56. Laboratory Records Department	151. Jay Cee Pigg
57. Laboratory Records, ORNL R.C.	152. J. F. Riley
58-82. E. T. Arakawa	153-177. R. H. Ritchie
83. C. R. Baldock	178. H. C. Schweinler
84. R. E. Biggers	179. M. J. Skinner
85-109. R. D. Birkhoff	180. E. G. Struxness
111. T. E. Bortner	181. J. A. Swartout
112. T. A. Butler	182. J. E. Turner
113. J. S. Cheka	183. A. M. Weinberg
114. T. F. Connolly	184. C. D. Zerby
115-138. L. C. Emerson	185. G. M. Fair (consultant)
139. F. F. Haywood	186. J. C. Frye (consultant)
140. H. H. Hubbell	187. R. Hamm (consultant)
141. G. S. Hurst	188. W. H. Langham (consultant)
142. W. H. Jordan	189. E. P. Odum (consultant)
143. S. V. Kaye	190. R. L. Platzman (consultant)
144. G. W. Keilholtz	191. J. L. Stanford (consultant)
145. B. H. Ketelle	192. L. S. Taylor (consultant)

EXTERNAL DISTRIBUTION

193. N. F. Barr, Division of Biology and Medicine, AEC, Washington, D.C.
194. M. J. Berger, National Bureau of Standards, Div. 403, Washington, D.C.
195. W. E. Deeds, Department of Physics, University of Tennessee, Knoxville
196. H. Ehrenreich, General Electric Research Laboratories, P. O. Box 1088, Schenectady, N.Y.
197. U. Fano, National Bureau of Standards, Washington, D.C.
198. R. A. Ferrell, Physics Department, University of Maryland, College Park, Maryland
199. H. A. Fowler, Elec. Physics Section, National Bureau of Standards, Washington, D.C.
200. D. C. Hammer, NASA, Lewis Research Center, Cleveland 35, Ohio
201. E. D. Harris, Department of Physics, University of Tennessee, Knoxville
202. S. A. Lough, Division of Biology and Medicine, AEC, Washington, D.C.
203. L. Marton, 4515 Linnean Ave., N.W., Washington 8, D.C. (National Bureau of Standards)
204. H. Mendlowitz, National Bureau of Standards, Atomic Physics Division, Washington 25, D.C.

205. A. H. Nielsen, Department of Physics, University of Tennessee, Knoxville
206. H. R. Philipp, General Electric Research Laboratories, P. O. Box 1088, Schenectady, N.Y.
207. C. J. Powell, National Bureau of Standards, Washington, D. C.
208. O. P. Rustgi, Electromagnetics Laboratory Research Department, Northrop Space Laboratories, 1111 E. Broadway, Hawthorne, California
209. J. A. Simpson, 312 Riley St., Falls Church, Virginia (National Bureau of Standards)
210. E. A. Stern, Department of Physics, University of Maryland, College Park, Maryland
211. E. A. Taft, General Electric Research Laboratories, P. O. Box 1088, Schenectady, N.Y.
212. Ye-Yung Teng, Department of Physics and Astronomy, University of Maryland, College Park, Maryland
213. G. L. Weissler, University of Southern California, Department of Physics, Los Angeles 7, California
214. P. R. Wessel, U.S. Naval Ordnance Laboratory, Silver Spring, Maryland
215. R. W. Wood, Division of Biology and Medicine, AEC, Washington, D.C.
216. H. O. Wyckoff, 9208 Whitney St., Silver Spring, Maryland (National Bureau of Standards)
217. Research and Development Division, AEC, ORO
- 218-854. Given distribution as shown in TID-4500 (20th ed.) under Physics category (75 copies - OTS)